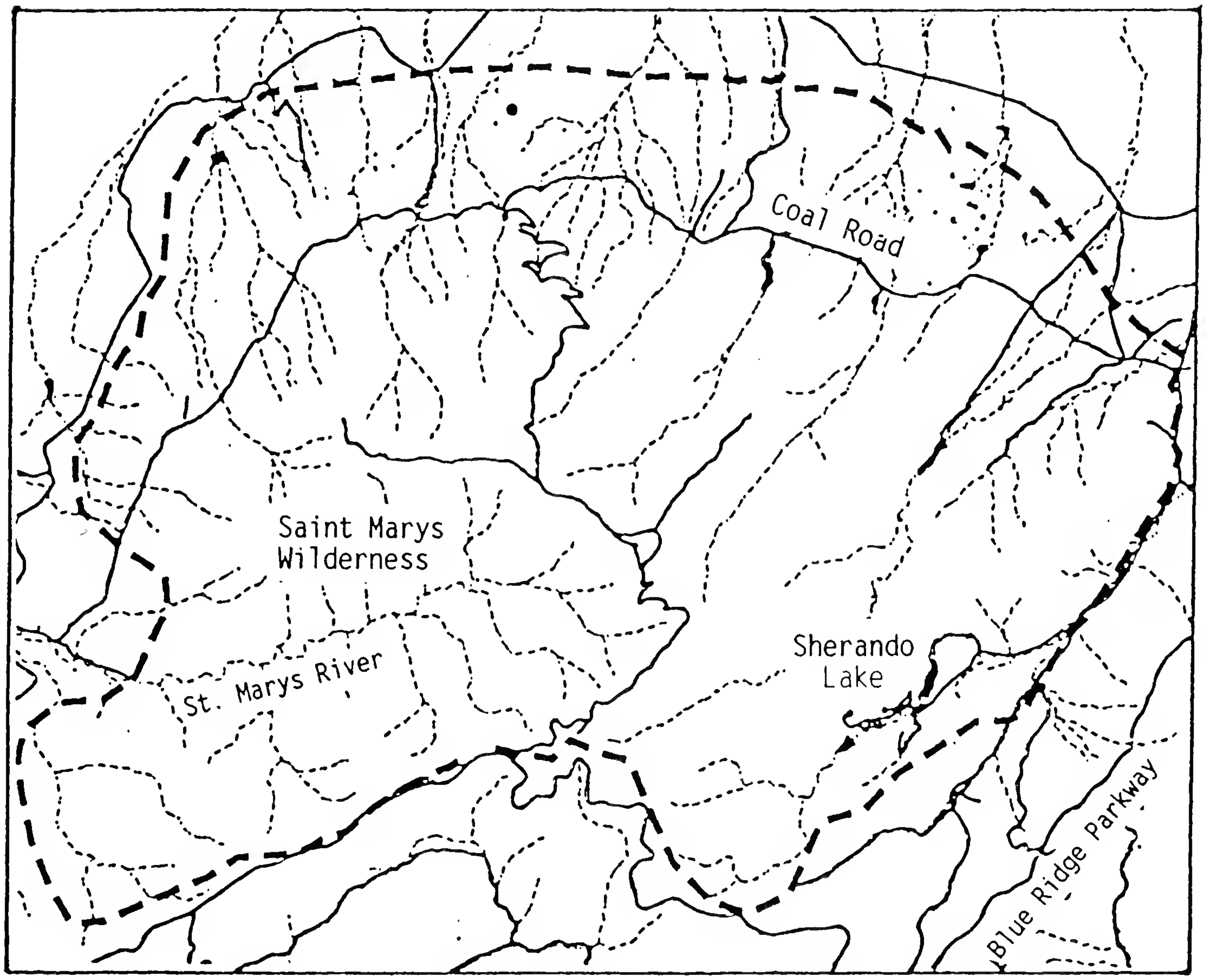
BANISTERIA

A JOURNAL DEVOTED TO THE NATURAL HISTORY OF VIRGINIA



The Big Levels Region of Virginia

Proceedings of a Symposium

The natural history of this unique area is documented in 16 papers in this special issue

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The Big Levels Region of Virginia:

Aspects of Natural History and Management of a Unique and Imperiled Area

Proceedings of a Symposium
Convened at Charlottesville, Virginia
October 16, 1998
Under the Auspices of the
George Washington and Jefferson
National Forests, and the
Virginia Natural History Society

VNHS Officers

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Introduction to the Symposium on the Natural History of the Big Levels Area: Shenandoah Valley Sinkhole Ponds and St. Marys River

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Combined results of multidisciplinary studies of a single geographic area often reveal patterns and interactions that cannot be discovered by single focus studies. The Great Dismal Swamp, for example, has been the subject of symposia held in 1911, 1974, and 1997. Proceedings of the last two symposia were published in book form (Kirk, 1979; Rose, 1999). The various chapters in these books solidified management and scientific interest in the Swamp and demonstrated the uniqueness of the area. The Big Levels area of southeastern Augusta County, Virginia, contains several types of aquatic and terrestrial habitats that have received variable amounts of attention over the past 70 years. Until now, academic researchers and resource managers have focused largely on their own discipline, in some cases accumulating considerable information on their target species, species group, or physical system. No one has reviewed all the available published and unpublished information, and indeed some of that information has not been assembled into documents or other sources accessible to others interested in the area. In the mid-1990s, we became aware that a large body of information had been accumulated from studies conducted in various parts of the Big Levels area. Our interest in determining what work had been conducted in this area developed into the establishment of the first symposium on this region of Virginia. The results of this symposium contained in the papers published in this issue of *Banisteria* demonstrate collectively that the Big Levels area is one of the most unique natural areas in the state.

The symposium held on 16 October 1998 consisted of 16 papers on a wide variety of topics ranging from wildlife management to geology to flora and fauna. Of these, 13 were submitted as papers for this issue of *Banisteria*. One paper on the geology of the alluvial fans near Stuarts Draft was already in press (Whittecar & Duffy, in press; also see Whittecar et al., 1999 abstract) and was replaced with the paper on the hydrology and geomorphology of Green Pond (Whittecar & Lawrence, 1999). We invited Scott Klopfer to submit his analysis of the climate of the Big Levels area after discovering that he had an existing data set and could derive a paper from his Master's thesis to provide yet another dimension to our coverage of the area. The resulting set of papers provides a thorough review of the body of knowledge that now exists for this region of Virginia. In addition, the information in these papers all point to the fact that the Big Levels area has been more intensively studied than previously recognized by the scientific and resource management communities.

The papers for this symposium proceedings were designed to stand alone as separate published contributions in a peer-reviewed journal. That way, authors could provide information that supported their

perspective and not have to cite the symposium introduction or other papers extensively. All papers were reviewed by at least one, usually two, reviewers and the primary editor for this issue (JCM).

The Big Levels area is a approximately12,950 ha region of the Blue Ridge Physiographic Province contained within the George Washington National Forest's Pedlar Ranger District. The St. Marys Wilderness Area lies within Big Levels, as does a high elevation natural, freshwater pond (Green Pond), and a series of natural sinkhole ponds (Fig. 1). Big Levels is a series of flat-topped mountains (Cellar Mt., Kelly Mt., Kennedy Ridge) that reach an elevation of about 990 m. The name "Big Levels" comes from the flattened mountainous topography. Major drainages include the St. Marys River in the southwestern portion and numerous streams that drain the upper elevations of Big Levels largely to the north. Alluvial deposits from ancient weathering processes created fans of Antietam quartzite cobbles in a sand, silt, and clay matrix overlying carbonate limestone some 50-150 m below the surface. Collapse of limestone in some places on these terraces helped create natural surface depressions that fill with water and exist as vernal pools. The Coal Road is an all-season access road, unless washed out by winter rains and snow melt, that skirts the upper region of the area. Recreational opportunities were enhanced in this region with the construction of Sherando Lake during the Civilian Conservation Corps era in 1935-1936.

The long-term history of Big Levels is one of geological change. The St. Marys River apparently flowed northward into the present day Shenandoah River over 140,000 years ago before being captured by the South River that flows into the James River, as documented by Bank et al. (1999). Erosion of the mountains along Big Levels in the Pleistocene and Miocene periods created the alluvial fans that are now dotted with sinkhole ponds (Whittecar et al., 1999). The topography, orientation, and geographic position in Virginia contribute to the relatively cold climate characteristic of the Big Levels area (Klopfer, 1999).

The pre-history and modern history of Big Levels include Native American use of the area as a hunting ground (Tolley & Barber, 1999) and intensive development using game management techniques in the 1930s through the 1980s (Swartz & Kocka, 1999). Human occupation of the area dates back about 12,000 years. Modern use of the area includes the development of early game management and conservation programs. Currently, the area is used extensively by local citizens and recreationists, and is managed in a multiple use context by the U.S. Forest Service.

The Shenandoah Valley sinkhole pond system occurs in a series of three clusters of ponds largely on U.S. Forest Service land. This pond system was once much more extensive in the Shenandoah Valley but many ponds have been lost due to agricultural practices and urbanization. One large pond noted by Carr (1940) that contained rare plants at that time is now a public recreational swimming pool. Buhlmann et al. (1999) provide detailed descriptions and photographs of 36 of these sinkhole ponds and evaluate the conservation biology of this system. Downey et al. (1999) demonstrate that the acid precipitation in the region is also affecting the sinkhole ponds and may be a problem in the future.

The flora of the sinkhole ponds has been studied by botanists since the 1930s and Spring Pond is famous for its disjunct and rare flora. Fleming & Van Alstine (1999) provide detailed descriptions of the plants and analyze the floristic communities in the Big Levels area. Knox et al. (1999) evaluate the distribution and abundance of one rare, and now federally listed, plant, the endemic Virginia sneezeweed (*Helenicum virginicum*). The animal fauna has not been as well studied as the flora. Three contributions expand our knowledge of dragonflies and damselflies (Roble, 1999), amphibians and reptiles (Mitchell & Buhlmann, 1999), and small mammals (Reynolds et al., 1999). The rich odonate fauna contains several rare and disjunct taxa, and one species of amphibian, the state endangered tiger salamander (*Ambystoma tigrinum*) occurs in several of the ponds. The combined flora and fauna of the Shenandoah Valley sinkhole pond system is a unique mix of species found nowhere else in Virginia or the Appalachian region.

St. Marys River is now famous for its impoverished invertebrate and fish faunas. The watershed was degraded severely by mining in the 1800s and early 1900s, although the river still maintained an apparently pristine aquatic fauna. Acid precipitation has since become a severe problem for the aquatic life in the St. Marys River. Webb & Deviney (1999) describe the changes in water chemistry over an eight year period in this stream and demonstrate that the river has indeed acidified. Surber (1951) conducted the first scientific sampling in the river and documented the invertebrate fauna, trout distribution, and salamanders in the late 1930s. His data set serves as the baseline against which changes in the abundance of these animals have been assessed. The documented changes in the benthic invertebrate fauna (Kaufmann et al., 1999) and the fish fauna (Bugas et al., 1999) demonstrate how detrimental acid precipitation has been in the system. Kirk & Mitchell (1999), however, show that the streamside salamander fauna has not been as affected as the other two groups. They show that salamander distribution in the St. Marys may be more affected by the presence of brook trout (*Salvelinus fontinalis).*

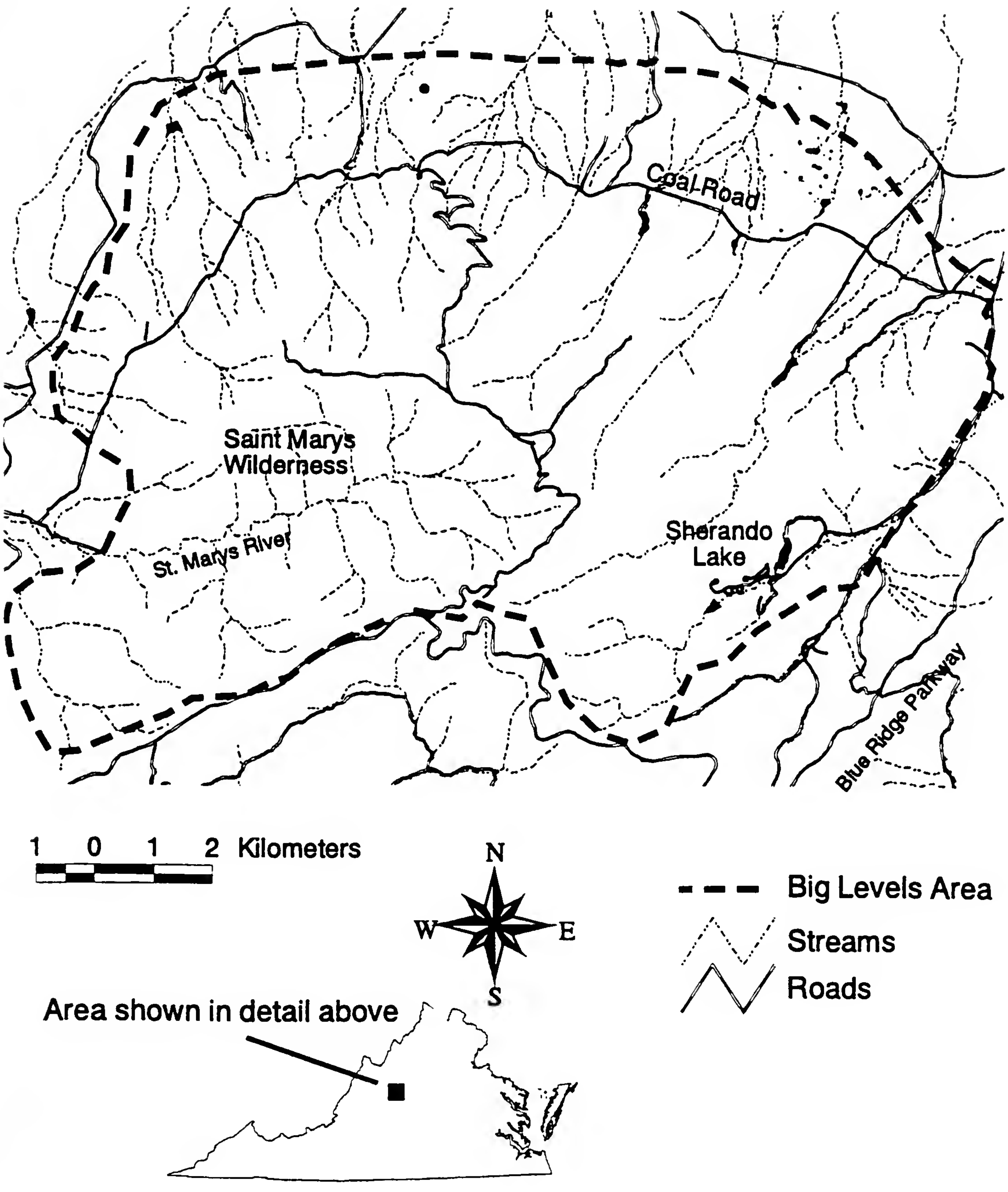

Fig. 1. Map of the Big Levels region in southeastern Augusta County, Virginia, showing the Shenandoah Valley sinkhole pond system, St. Marys River, and other prominent features.

Green Pond is an isolated, shallow pond located at an elevation of about 976 m on the top of Kennedy Ridge. Whittecar & Lawrence (1999) describe the hydrology and geomorphology of this spring-fed pond and demonstrate that water level fluctuations have been extensive over the past two decades, including several periods of complete pond drying.

Resource managers and others interested in the natural resources of this area should read all of these papers. Readers will realize quickly that every author shares a wealth of knowledge of the Big Levels area and that the uniqueness of the region should be maintained and preserved in as natural a state as possible. Readers will also realize that we must maintain long-term monitoring

of acid precipitation and its effects on sensitive animals and plants, as well as remain vigilant to the changes that are bound to occur to rare species and habitats with the encroachment of increasing number of people who are moving into and using the area. Conservation efforts on behalf of the Big Levels area should take a multi-disciplinary approach and be planned for the long-term. Issues such as acid precipitation effects, liming, illegal motorized vehicle use of the area, illegal logging for firewood, garbage dumping, poaching, timbering programs, and restoration efforts should be evaluated with respect to the conservation value of the region. We recommend that a team of forest service managers, appropriate state agency personnel, scientific researchers, and conservation biologists be organized to serve as an advisory group to the U.S. Forest Service that oversees activities in the Big Levels area.

ACKNOWLEDGMENTS

We thank all the presenters of papers at the symposium and the authors of papers in this issue of *Banisteria* for their professional presentations and papers, and for their timely response to the editorial process. All papers were in final form nearly six months to the day after the symposium of October 16. We are grateful to the following governmental agencies for their support of the symposium: George Washington and Jefferson National Forests, Virginia Department of Conservation and Recreation's Division of Natural Heritage, Virginia Department of Game and Inland Fisheries, and the Virginia Division of Forestry. The latter provided the meeting room gratis, and the other agencies provided financial support for the publication of this issue of *Banisteria.*

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Wildlife Management Activities in Big Levels, Augusta County, Virginia: An Overview

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INTRODUCTION

Southeastern Augusta County, Virginia, referred to as "Big Levels", is a rough series of connected flat-topped mountains west of and somewhat isolated from the Blue Ridge Mountains. As their name suggests, the mountain summits are generally flat or gently rolling, eventually giving way to steep or moderately-sloped ridges with thick vegetation, rugged talus slopes, barren rock outcrops, and dense thickets until reaching more moderate terrain below. The bedrock geology ranges from quartzite to sandstone, but the lowest elevations override deep limestone formations. Springs and flowing streams are abundant over most of the Big Levels area. Numerous natural ponds or vernal pools exist at lower elevations. Big Levels is comprised primarily of stands of hardwoods, including various species of oak (*Quercus* spp.), hickory (*Carya* spp.), black gum (*Nyssa sylvatica*), and yellow-poplar (*Liriodendron tulipifera*) interspersed with pitch pine (*Pinus rigida*). The steeper slopes contain more chestnut oak (*Quercus prinus*), bear oak (*Quercus ilicifolia*), and thickets of mountain laurel (*Kalmia latifolia*), greenbriar (*Smilax* spp.), blueberries (*Vaccinium* spp.), and table-mountain pine (*Pinus pungens*). Thick stands of bear oak and mountain laurel occur at the highest elevations. Some magnificent stands of eastern hemlock are abundant along watercourses. American chestnut (*Castanea dentata*) was among the dominant species in most of Big Levels area but is now replaced with oaks and other hardwoods.

Pre-1900s

Historically, the Big Levels area was only marginally used for agriculture or grazing due to its poor soil productivity; most of this activity occurred along its fringes in the valley. The area is believed to have been a highly prized hunting ground by Native Americans because of its abundant wildlife populations (Thornton, 1969). All of the tribes in the Blue Ridge area assembled there for their winter hunts (USDA-Forest Service, 1941). Wildlife populations were subjected to significant exploitation once white settlers arrived. Sporadic attempts at mining iron and manganese deposits were made and abandoned in the 1800s and early 1900s. During this same period, the primary economic use was the extensive harvest of hardwoods to provide charcoal for at least five local iron furnaces. The few people who lived in the area subsisted by farming, hunting, berry picking, and probably moonshine production (Thornton, 1940). The last of the original herd of native deer on Big Levels was extirpated by a party of eight hunters during a severe winter in the early 1890s (USDA-Forest Service, 1941;Thornton, 1969).

1900-1940

The local wildlife conservation movement during the early 1900s was initiated by private conservation groups (e.g., Waynesboro Game and Fish Protective Association, Augusta County Fish and Game Association) to preserve and manage depleted or extirpated native wildlife populations. Creation of government agencies like the Virginia Commission of Game and Inland Fisheries, the U. S. Forest Service, and the U. S. Biological Survey (now the U.S.G.S. Biological Resource Division) resulted in preservation of wildlife habitat and professional wildlife management. A cooperative agreement in 1924 between the state of Virginia and the U.S. Government eventually led to the establishment of the 1,619 ha Big Levels State

Game Refuge in 1930 (Thornton, 1940). The state refuge was bounded roughly by the Coal road, Kennedy Ridge, Green Pond, and the headwaters of Falling Rock Creek see Fig. 1 in Mitchell et al. (1999).

Due to insufficient funds, the Game Commission was unable to completely fulfill its management obligations to conserve, protect, replenish, propagate, and increase the population of game birds and animals on this refuge. Responding to petitions and recommendations of sportsmen and interested citizens to greatly increase the refuge size and place it under federal administration, the Game Commission took the unusual position of endorsing President Roosevelt's July 1935 proclamation. With an additional 11,331 ha, the proclamation established the Big Levels Game Refuge within the George Washington National Forest, to be administered by the U. S. Forest Service (USDA-Forest Service, 1941). The proclamation required that the area "be set aside for the protection of game animals, birds, or fish; and whosoever shall hunt, catch, trap, willfully disturb or kill any kind of game animal, game or nongame bird, or fish, or take the eggs of any such bird on any lands so set aside, or in or on the waters thereof, except under such general rules and regulations as the Secretary of Agriculture may from time to time prescribe, shall be fined not more than $500 or imprisoned not more than six months, or both". In March 1936, the Virginia General Assembly enacted Chapter 316 thereby transferring all rights concerning wildlife in Big Levels to the U.S. Government. To date, this law has never been rescinded. However, as described below, since the 1950s Big Levels has been managed similar to other national forest lands and not as a refuge. The refuge was originally established as both a demonstration area and an experimental area where wildlife problems could be researched cooperatively by State, Federal and private agencies.

The U.S. Forest Service and the Game Commission learned many lessons about cooperative management during the early years on Big Levels. From these lessons, a Cooperative Agreement between these two agencies was established in 1938 (Thornton, 1969). Cooperative wildlife management increased with additional funding. In 1938, the Pittman-Robertson Act provided states with additional funds for wildlife management. The National Forest Stamp Act of 1938 also required those who hunt, fish, or trap on National Forest lands to purchase a special stamp. The one dollar fee was used to help fund law enforcement and wildlife habitat work.

The earliest wildlife management efforts on the area emphasized restocking of game species along with law enforcement and predator control, including control of free-roaming domestic dogs. White-tailed deer (*Odocoileus virginianus*), black bear (*Ursus americanus*), and beaver *(Castor canadensis*) were reintroduced by 1940. Thornton (1969) stated that Big Levels was the first location in Virginia where the stocking of white-tailed took place. However, Peery & Coggin (1978) and McDonald & Miller (1993) both indicate the first deer were stocked at a location in Rockingham County in 1926; both of these sources show 1933 as the first time that Augusta County received deer. Although of limited accuracy, population estimates were attempted before and after the stocking efforts on Big Levels (Table 1) (USDA-Forest Service, 1941). The entire boundary was wired and posted with signs. All access roads and trails were gated or closed permanently to general road traffic where feasible. Civilian Conservation Corps labor was used to improve roads and fire trails, construct water holes and lakes, plant erosion control trees and shrubs, establish salt licks for deer, build patrol cabins, and provide wildfire protection.

In the 1930s, biologists advocated developing sodded openings on 10% of the refuge area. These openings were seeded with various grasses and lespedezas, required little maintenance, and provided benefits to wildlife. Eventually about 81 ha were constructed, but the original goal of 10% was never achieved due to the high cost of clearing and development in the rough terrain (Thornton, 1969). For economic reasons, forest-wide clearing development is now generally done in association with active timber sales. The U.S. Forest Service constructed water impoundments and developed a recreation area that became the Sherando Lake Recreation Area. They also acquired land holdings within or close to the Big Levels Game Refuge to consolidate the land area (USDA-Forest Service, 1941).

Table 1. Estimated populations of selected species for 1935, 1940, and numbers stocked of selected species in Big Levels Game Refuge, Augusta County, Virginia.

SPECIES	1935 ESTIMATE	MINIMUM # STOCKED 1935-40	1940 ESTIMATE
White-tailed deer	30	56	320
Black bear	8	4	31
Beaver	0	2	4
Wild turkey	40	0	90
Ruffed grouse	300	0	700
Bobwhite quail	80	0	240

Many cooperative research projects were implemented on the refuge in its early years by wildlife biologists. Studies were conducted on ruffed grouse (Nelson et al., 1938), wild turkey (Martin et al., 1939), snakes (Uhler et al., 1939), and habitat development (Howard, 1938; Thornton, 1940; DeGarmo, 1941). Additional work not published from the area included the development of a new type of deer truck and holding pen, as well as a big game checking system (USDA-Forest Service, 1941; Thornton, 1969).

1940-1998

In 1955, a technique was developed for trapping native wild turkeys (*Meleagris gallopavo silvestris*). Big Levels was the first location where wild turkeys were captured for restocking other portions of their range (Coggin & Peery, 1975). During the late 1950s, black bear research involved trapping, measuring, and tagging for harvest during later hunting seasons (Harrison, 1958). This was the first trapping and tagging of black bears in the Commonwealth. Eventually, the refuge concept (i.e., no hunting) was gradually discarded as sustainable game populations increased and dispersed onto surrounding areas.

White-tailed deer became locally abundant in many areas, especially on adjacent farmlands and orchards of the Shenandoah Valley where crop damage was excessive and some action was required. In 1951, the first hunting season was allowed by the Game Commission for deer on Big Levels; it was a controlled hunt where the number of hunters was limited. This was the only place in Virginia where hunting pressure was controlled on national forest lands (Thornton, 1960). Antlerless deer were allowed to be harvested for the first time west of the Blue Ridge Mountains during the first three days of this five day season. A quota of 650 permits were issued, with a limit of 125 hunters per day. This resulted in 120 whitetails (85 antlerless) being harvested that year. U.S. Forest Service personnel collected harvest data at game checking stations at entrance/exit points for the area. The administrative problems associated with such a limited hunt eventually led to the opening of the area to all hunters by 1953. Deer were also trapped on Big Levels to be used for stocking other portions of the state. White-tailed deer populations, once plentiful on the refuge, were reduced by heavy hunting pressure for the first few years after the refuge was open to hunting. At the same time range conditions deteriorated because of much of the timber matured to pole stands (Thornton, 1969). These two factors led to the deer population being stabilized at lower levels. Although the intensity of the original wildlife habitat development program gradually lessened, the U.S. Forest Service maintained a vigorous law enforcement effort on the Big Levels area for a long time with use of special federal game wardens.

Cooperative efforts for habitat work continued for many years. Large areas of bear oak on the summit were released mechanically from competing tree growth. Actual dates of this work could not be documented but post-treatment evaluations were conducted as late as March 1983 (M. Carpenter, personal communication). When first acquired, the area possessed little timber of commercial value. With the maturation of timber, harvesting was begun to develop even-aged forest stands and provide early succession habitat for wildlife. Growing markets for pole-sized hardwood timber created economic opportunities to cut stands in the area. Areas of eight ha or more were clearcut to be regenerated into even-aged stands of mixed pines and hardwoods (Thornton & Richards, 1968;Thornton, 1969). Funds derived from timber sales were often used for wildlife habitat improvements after completion of the sales. Timber harvesting provided a diversity of habitat for some wildlife species with stands of various ages instead of one age over the majority of the area. Increased understory growth and roads revegetated with grasses were other wildlife management benefits of these timber sales.

When the Big Levels Refuge was created, all access roads to Big Levels were closed to the public. Beginning in 1948, roads were opened to hunters and fishermen seasonally or only closed administratively during winter months. At present, the primary access roads are open most of the year. Although benefiting the public, road openings probably have been detrimental to wildlife and wildlife management. Vandalism, littering, dumping, poaching, and other human disturbances have been prevalent in recent decades.

In the 1980s and 90s, the public's environmental awareness shifted toward preservation. The wilderness movement stimulated the creation of the St. Marys Wilderness Area in 1984. This 4,087-ha watershed had occupied a large portion of the Big Levels Game Refuge created in 1935 but was difficult to manage due to its rugged topography. The wilderness concept provided primitive (non-mechanized) recreation experiences and solitude while preserving the natural environment and the scenic, scientific, educational, and historical values of the area. The most recent forest plan designates most of Big Levels between the Coal Road and the St. Marys Wilderness Area as a Special-Interest Area for its unique biological resources (USDA-Forest Service, 1993). The policy for special-interest areas allows maintenance of existing or replacement of wildlife improvements as long as their presence is compatible with management objectives. Vegetation can be manipulated for management of

biological values including threatened, endangered, or sensitive species and their habitat. Prescribed burning is allowed to meet objectives for habitat management and species maintenance. The area is classified as unsuitable for timber production. Parts of the Shenandoah Valley sinkhole pond system area, north of the Coal Road, is managed as a proposed Research Natural Area at present. Most of the other land north of the Coal Road is managed as early successional forested habitats for wildlife. Wildlife management in these areas has an objective of maintaining at least 5% of the area in grassy or herbaceous openings for deer or ruffed grouse. Timber harvests must average 3-4 ha and not exceed 8 ha. The Sherando Lake and Back Creek watershed are included in a dispersed recreation designation which allows for maintenance of existing wildlife improvements and limited timber management like group selection or individual tree cuttings, salvage cuts, or sanitation cuts, but only on nearly level terrain.

SUMMARY

The Big Levels area is recognized as a unique place where the cooperative wildlife management program began between the U. S. Forest Service and the Virginia Game Commission. The refuge was used as a demonstration area to test many new game management ideas, techniques, and regulations that are standards today. Among the "firsts" for Virginia which took place on Big Levels was the first controlled deer hunt, the first antlerless deer hunting west of the Blue Ridge Mountains, the first big game checking system, the first live-trapping of wild turkeys for stocking purposes in Virginia, and the first live trapping and tagging of black bear. As refuges were established in other areas of the National Forest to reintroduce and manage wildlife, they were all eventually integrated back into the same management plans as the rest of the forest. The early, labor intensive efforts to manage wildlife on relatively small areas developed into a more economical, landscape level approach to wildlife management on the entire National Forest.

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Climate Characteristics of the Big Levels Region, Augusta County, Virginia

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INTRODUCTION

Navarra (1979) defined climate as the specific set of statistics that describe weather conditions during a specified interval of time. It is the most important abiotic factor influencing the distribution of plant and animal communities and species (Holdridge et al., 1971; Vernberg & Vernberg, 1970). Major weather factors that comprise climate include, but are not limited to, temperature, precipitation, air pressure, humidity, wind, evapotranspiration, and solar radiation (Thornwaite & Mather, 1955). Topography and geographic location greatly influence climate characteristics of a given area (Sartz, 1972). Climate has been cited as influencing species distribution in Virginia (Woodward & Hoffman, 1991).

The Big Levels region (Fig. 1) located in Augusta County, Virginia, occurs in the Blue Ridge physiographic province (Bailey, 1980) and is characterized by mountainous terrain between the Shenandoah Valley to the west and the Piedmont province to the east. The Big Levels area is affected by both oceanic and continental weather patterns due to its elevated position on the Blue Ridge (Woodward & Hoffman, 1991).

Climatic information is difficult to obtain at a local level due to the cost of monitoring and compiling weather information. Such data should be compiled over extended periods of time, however, few studies are conducted at a temporal scale of sufficient length to assess climate patterns adequately. The closest National Oceanic and Atmospheric Administration (NOAA) weather station to Big Levels is located in Montebello, over 400 m lower in elevation. This station only records precipitation data. Regional climate can be estimated and modeled by using a geographic information system (GIS) (Ford, 1982; Cooter et al., 1993; Pakeman & Mars, 1996; Scalet et al., 1996). Klopfer (1997) provided estimates of landscape-scale temperature, precipitation, potential evapotranspiration (PET), and moisture for Virginia. In this paper I describe the climate characteristics of the Big Levels region and illustrate the unique climate diversity of the area relative to the rest of Virginia.

MATERIALS AND METHODS

I estimated mean monthly temperature, precipitation, PET, and annual moisture at each 300 m x 300 m pixel in Virginia. I estimated temperature and precipitation by inverse-distance interpolation from 30 years of data collected by NOAA (Owenby & Ezell, 1992) for weather stations in Virginia and nearby stations in neighboring states (Klopfer, 1997). I adjusted estimates for differences in elevation before interpolation with an adiabatic cooling rate. This rate was calculated by dividing the difference in temperature by the difference in elevation for the highest and lowest of the five closest weather stations surrounding each pixel (Klopfer, 1997). I estimated monthly PET using the method described by Thornwaite & Mather (1957). An index of moisture was obtained from monthly temperature estimates and PET (Carter & Mather, 1966). I evaluated the accuracy of temperature and precipitation estimates by comparing estimates to actual data from NOAA stations not used in the estimation process. PET estimates were compared to PET calculated from NOAA station data.

All GIS operations were performed on a Microsoft Windows-based personal computer. The GIS software used was TNT-Mips (MicroImages, Inc., 201 North 8th Street, Suite 15, Lincoln, Nebraska 68508-1347). All statistical computations were performed in SAS (SAS Institute Inc., Box 8000, SAS Circle, Cary, NC 27511-8000). Base digital elevation data were obtained from the United States Geological Survey.

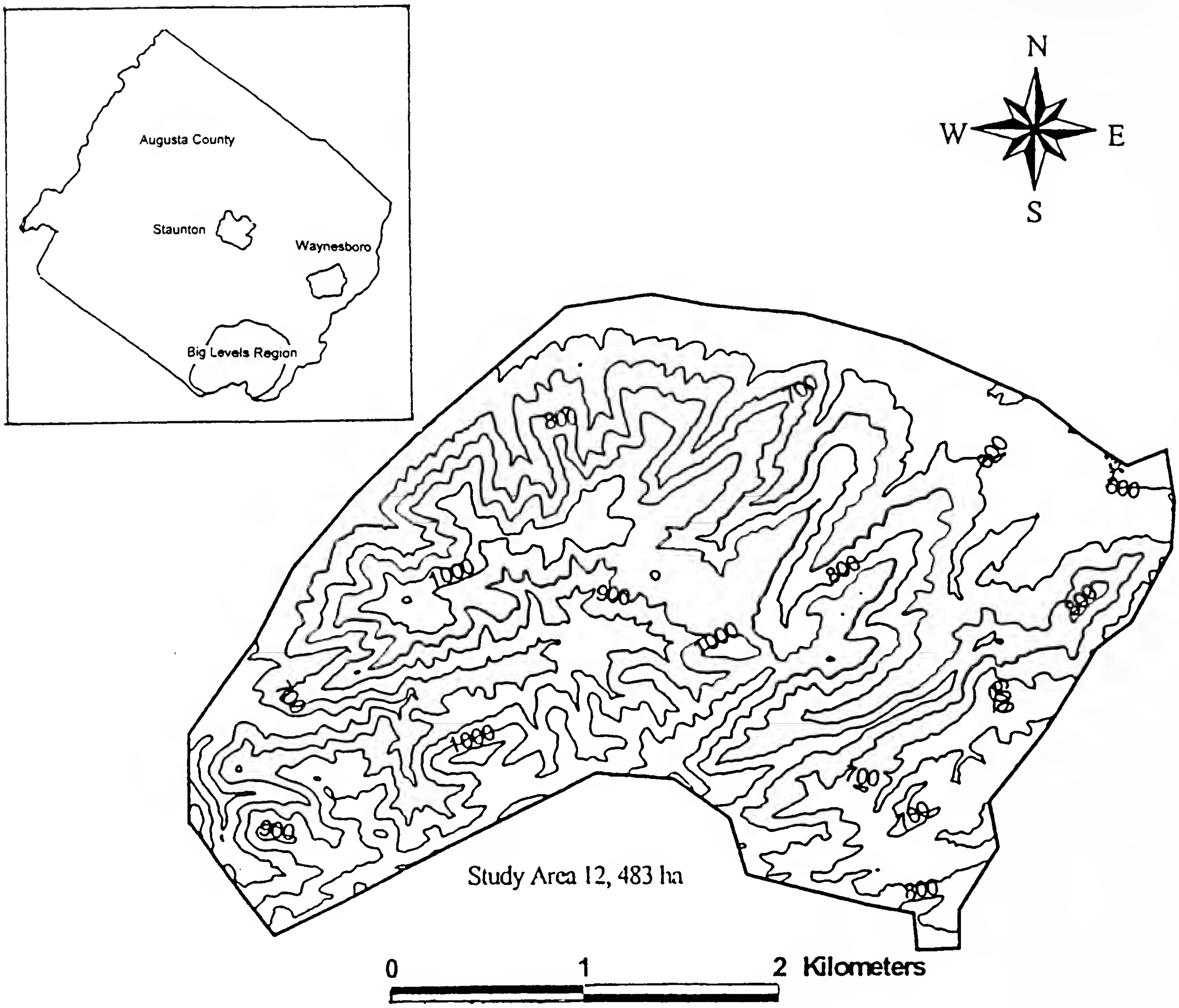

Fig. 1. The elevation contours (m) of the Big Levels region. Climate estimates reported correspond to the boundary depicted above.

Climatic characteristics reported for the Big Levels region were taken from the entire state climate data set shown in Fig. 1 (approximately 12,500 ha). I tabulated minimum, mean, and maximum values for mean monthly temperature and precipitation, and compared climate characteristics of Big Levels to those of the entire state.

RESULTS

Mean monthly temperatures for the Big Levels region ranged from a minimum of -10.5°C in January to a maximum of 21.9°C in July (Table 1). Within a given month, the range of mean monthly temperatures for Big Levels averaged 8.5°C, but mean monthly temperatures in October differed by 10°C. The Big Levels region is on average 6°C cooler then the mean monthly temperature calculated for the state (Table 1). Mean monthly temperature is closely tied to elevation, with higher elevation areas remaining below freezing well into March.

Mean monthly precipitation ranged from 66 mm in January to 107 mm in July (Table 2). Mean monthly precipitation in the Big Levels region did not vary dramatically within any month (maximum of 10 mm in August), and did not differ greatly from state averages for any month (mean difference of 7 mm).

Temperature and precipitation of the Big Levels area were combined in a climatograph (Fig. 2) to illustrate the difference between the Big Levels local climate and the

Table 1. Average of 30-year mean monthly temperature (° C) and differences for Big Levels and Virginia.

	Big Levels			Virginia			Difference		
Month	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
January	-10.5	-5.4	-1.9	-11.4	0.7	5.2	-0.9	6.1	7.1
February	-8.6	-3.8	-0.3	-9.5	2.3	6.3	-0.9	6.1	6.6
March	-2.2	-2.1	5.0	-4.1	7.3	10.3	-1.9	9.4	5.3
April	-0.6	5.3	9.4	-2.0	12.2	15.5	-1.4	6.9	6.1
May	6.7	12.1	15.3	4.4	17.0	20.5	-2.3	4.9	5.2
June	11.7	17.0	19.7	9.5	21.3	24.3	-2.2	4.3	4.6
July	14.2	19.2	21.9	12.1	23.5	26.3	-2.1	4.3	4.4
August	14.0	18.5	21.1	10.4	22.9	25.8	-3.6	4.4	4.7
September	7.9	13.8	17.0	5.4	19.3	23.0	-2.5	5.5	6.0
October	0.4	7.4	11.0	-2.4	13.3	17.5	-2.8	5.9	6.5
November	-4.7	1.2	5.2	-5.7	8.2	12.4	-1.0	7.0	7.2
December	-6.6	-2.5	0.5	-7.4	3.1	7.8	-0.8	5.6	7.3

state climate. PET and precipitation were compared in a water balance graph (Fig. 3). This pattern is typical (Thornwaite & Mather, 1955) of humid regions of the continent.

DISCUSSION

GIS-based landscape climate modeling provided sound estimates for all climate variables modeled in this study. Until more comprehensive climate data are recorded in this and other regions of the State, GIS climate modeling can provide reasonable, economical, and effective estimates for specific areas without long-term data. Mean monthly temperature estimates for Virginia were accurate within 1°C and precipitation estimates were accurate to within 13 mm (Klopfer, 1997). I assume that the accuracy of the estimates for the Big Levels region reflect that accuracy. Unfortunately, the estimates were verified with NOAA weather stations that are typically located in urban centers and at relatively low elevations. Thus, reported accuracy of temperature and precipitation may not be as accurate for the Big Levels regions due to its elevated position relative to the surrounding weather stations.

Although mean monthly temperature varies across the Big Levels region, precipitation does not. This could be a result of including elevation differences in the temperature estimation procedure but not in the precipitation estimates. Topographic influences on precipitation within the Big Levels region, if present, were not incorporated in this study. The Big Levels region appears to receive more rain than the state average in Winter and Spring seasons,

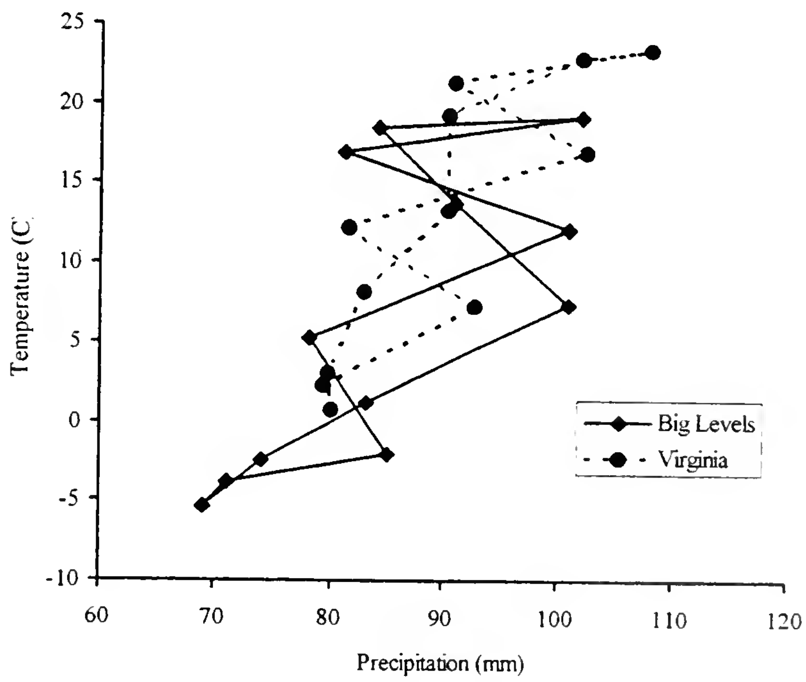

Fig. 2. Climatograph illustrating that the Big Levels region is colder and wetter than the rest of Virginia. Note the relative position of the two polygons, with the Big Levels polygon skewed slightly right and lower on the X and Y axes, respectively.

Table 2. Average of 30-year mean monthly precipitation (mm) and differences for Big Levels and Virginia.

	Big Levels			Virginia			Difference		
Month	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
January	66	69	73	50	79.9	110	-16	10.9	37
February	67	71	75	51	79.3	109	-16	8.3	34
March	82	85	89	68	92.7	128	-14	7.7	39
April	76	78	80	60	81.5	116	-16	3.5	36
May	99	101	105	82	102.5	131	-17	1.5	26
June	77	81	84	69	90.9	118	-8	9.9	34
July	99	102	107	78	108	141	-21	6	34
August	90	84	100	74	102.1	140	-16	18.1	40
September	87	91	95	70	90.3	135	-17	-0.7	40
October	97	101	106	67	90.4	133	-30	-10.6	27
November	81	83	86	66	82.8	132	-15	-0.2	46
December	71	74	77	53	79.7	115	-18	5.7	38

and less rain during the Fall (particularly in October). In Summer (June - August), the maximum amount of precipitation is less than the state mean for the same months.

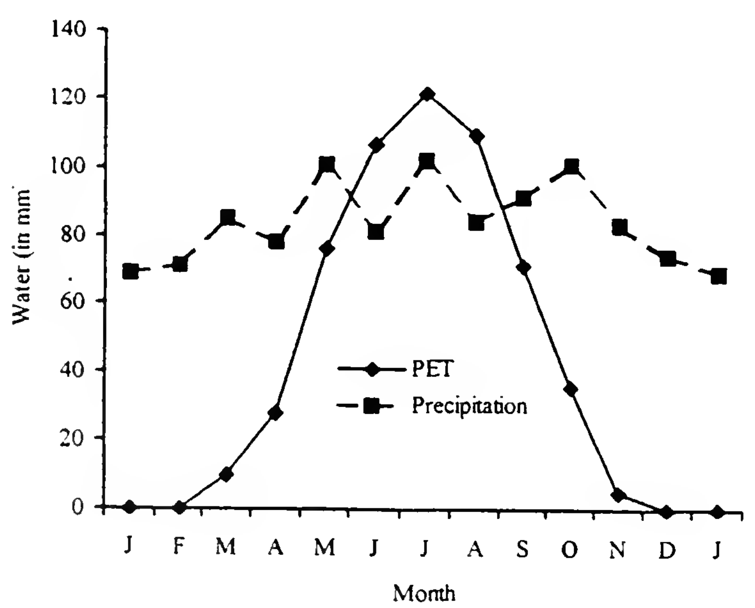

Fig. 3. Annual water budget for the Big Levels Region. In months where PET is lower than precipitation ground water is recharged to capacity. Excess water runs off until PET is greater than precipitation, then ground water is used to meet evapotranspiration requirements. When PET falls below precipitation ground water is recharged.

This corresponds to the slight water deficit evident in Fig. 3.

The Big Levels region has a complex climate that is cooler and wetter than most other areas in Virginia. The size of the region is relatively small yet has a range of temperatures capturing half of the variation observed over the entire state in any given month. For comparison, the range of annual mean temperature for the Big Levels region (7.8°C) was larger than ranges observed for the Mount Rogers area (5.7°C), the Burkes Garden area (3.9°C), and the region encompassing Massanutten Mountain and central Shenandoah National Park (6°C). This difference is especially important when the size of the land areas from which the ranges were derived are considered. The range of temperatures reported for Big Levels was from a land area of 12, 483 ha. This area is very small compared to the areas used for Mount Rogers (148, 233 ha), Burkes Garden (24, 843 ha), and Massanutten-central Shenandoah National Park (288, 744 ha).

This variation creates unique conditions for certain plant and animal communities typically restricted to higher elevations or more northerly latitudes. The geographic distribution of plant communities has been shown to be largely a function of temperature and precipitation (Waring, 1969; Holdridge et al., 1971; Whittaker, 1975;

Bailey, 1980; Woodward, 1990). The Big Levels region provides climatic habitat for communities not found in either the Shenandoah Valley or the Piedmont. Studies of local plants, amphibians, reptiles, and invertebrates support this view (Flemming & Van Alstine, 1999; Mitchell & Buhlmann, 1999; Roble, 1999). When viewed at a large scale (50,000 – 100,000 ha), the Big Levels region, combined with the regions immediately adjacent to it, is the most climatically diverse landscape in Virginia.

ACKNOWLEDGEMENTS

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Descriptive Ecology of the Shenandoah Valley Sinkhole Pond System in Virginia

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INTRODUCTION

Sinkhole ponds in the Shenandoah Valley Sinkhole Pond (SVSP) system are found along the bases of western-facing slopes of the Blue Ridge Mountains in Virginia, and extend from Augusta County north to Page County, a distance of approximately 89 km. These ponds exist in colluvial and alluvial terrace deposits that consist of poorly sorted Antietam quartzite cobbles and boulders in a loosely compacted matrix of sand, silt, and clay that have been eroded from the slopes of the mountains (Duffy, 1991; Kochel, 1987; 1992; Whittecar & Duffy, 1992). These deposits can be from 100 to 500 feet thick (Hack, 1965) and lie over a thick section of relatively weak, westward-dipping carbonate limestone strata of Cambro-Ordovician age. Solution of the valley floor limestone underneath results in the formation of sinkholes; accumulated clay layers and the alluvial deposits sometimes form impermeable layers that enable the sinkholes to retain water. Age estimates for the alluvial fan deposits based on soil profiles support an early to late Pleistocene age (Whittecar & Duffy, 1992). Pollen profiles from the bottom sediments of one of the ponds (Spring Pond) indicate that the ponds have existed for over 15,000 years (Craig, 1969). Due to different hydrologies, some of the sinkhole ponds may have ground water connections, while others fill from surface runoff. The range in hydroperiod includes permanent to highly ephemeral ponds.

The SVSP system contains a unique assemblage of coastal plain and northern bog plant species and may represent relict communities of Tertiary flora (Carr, 1937, 1937-38; Gorey, 1984; Fleming & Van Alstine, 1999). Disjunct coastal plain and northern floral elements total 93 species, 27 of which are listed as endangered, threatened, or rare in Virginia (Virginia Division of Natural Heritage, 1990). The federally endangered swamp pink (*Helonias bullata*) and the federally threatened and state endangered Virginia sneezeweed (*Helenium virginicum*), an Augusta County sinkhole pond endemic, occur here. Rare animal species include the state endangered eastern tiger salamander (*Ambystoma tigrinum*), a coastal plain disjunct (Buhlmann & Hoffman, 1987; Pague & Buhlmann, 1991). The only populations of spotted turtles (*Clemmys guttata*) found west of the Blue Ridge occur in

the sinkhole ponds and associated wetlands of Augusta County (Mitchell, 1994). The great diversity of dragonflies (Odonata) ranks the SVSP system as one of the most biologically significant areas in Virginia for this insect group (Roble, 1999).

Although individual sinkhole ponds are scattered north along the western flank of the Blue Ridge at Dooms, Crimora, Hairston, Deep Run, and Madison Run, the largest concentration and best protected series of ponds exists on large terrace deposits on and adjacent to the George Washington National Forest, Pedlar Ranger District, Augusta County, Virginia. All ponds addressed in this paper lie north of the Coal Road at an elevation of approximately 540 m (Fig. 1). The three groups of ponds are described in this paper as the Maple Flats, Loves Run, and Sherando Pond Complexes (Figs. 2-4). They occur in an approximately 16 km section along the base of the northern flank of the Big Levels Area (Sherando and Big Levels 7.5 minute topographic quadrangles).

Natural forest habitat on the terraces and alluvial fans surrounding these ponds consists primarily of chestnut oak (*Quercus montana*), white oak (*Q. alba*), and other hardwoods like hickory (*Carya* spp.) and red maple (*Acer rubrum*). Virginia pine (*Pinus virginiana*), shortleaf pine (*P. echinata*), and pitch pine (*P. rigida*) are interspersed on the dry, acid, and nutrient-poor soils. Stands of planted white pine (*Pinus strobus*) appear throughout the area.

Wildlife management activities have occurred on the George Washington National Forest (GWNF) since 1924. The Big Levels Game Refuge, within the GWNF, was established in 1930. During that decade, a number of botanical investigations focused on Spring Pond in the Maple Flats Pond Complex, but also reported information on other sinkhole ponds in the area (Carr, 1937; Carr 1938; Rawlinson & Carr, 1937). Between 1936 and 1941, game species including deer, bear, beaver, turkey, grouse, and quail, were stocked by the VDGIF (Schwartz and Kocka, 1999). Two ponds were created as waterfowl impoundments in the Maple Flats area adjacent to Canada Run in the 1950s (R.H. Giles, pers. comm.). Aerial photographs dated September 1937 (National Archives and Records Administration, College Park, Maryland; Fig. 6c) indicate that several small, boggy wetlands existed on the sites now occupied by those man-made ponds. Even-aged timber management began in the 1960s in the GWNF. As a result, a patchwork of clearcuts and planted pine stands, primarily consisting of white pine (*Pinus strobus*) are intermixed among 40 year-old stands of oaks and mixed hardwoods. Most of the SVSP system in the National Forest north of the Coal Road is currently designated as Management Area 16 with an emphasis on grouse management. There are two exceptions, however. The Maple Flats Pond Complex, currently placed in Management Area 4, is a candidate for designation as a U.S. Forest Service Research Natural Area, and the Loves Run Pond Complex is designated as a Special Interest Area (Smith, 1991). The area south of the Coal Road to the top of Big Levels was designated a Special Interest Area by the U.S. Forest Service in 1993.

In this paper, we present an individual descriptive account of each sinkhole pond within three pond complexes of the SVSP system. Our aim is to provide a brief overview of the physical and biological characteristics of all the natural ponds and examine this system in a landscape context. Variation in hydroperiod causes each pond to be unique in its species assemblage and is thus responsible for the significant biodiversity of each pond complex. Our findings demonstrate that in order to protect the integrity of the fauna and flora, the collective assemblage of ponds needs to be addressed in conservation and management planning.

Sinkhole Pond Accounts

The ponds we describe here are categorized into one of three major pond complexes: 1) Maple Flats (Ponds 1-19, including Spring Pond, Horseshoe Swamp, Elusive Pond, Kennedy Mountain Meadows, and the man-made ponds on Canada Run; Fig. 2, Plates 1-5); 2) Loves Run (Ponds 20-31; Fig. 3, Plates 6-7); and 3) Sherando (Ponds 32-36; Fig. 4, Plate 8). We compiled summaries of each pond from the historic literature, aerial photographs from 1937, 1979, and 1985, our own field notes, Virginia Division of Natural Heritage (DNH) files, Buhlmann (1987), and Buhlmann & Mitchell (1988). In creating Figures 2-4, we used aerial photographs to modify and correct errors in pond locations, sizes, and shapes depicted on the Sherando and Big Levels USGS 7.5 minute topographic quadrangles currently available. A few unlabeled ponds appear on our figures but are not discussed because no information on them was available. Each pond narrative is presented in the same general format: shape and size, structural description, surrounding habitat, pond vegetation, noteworthy flora, known hydrology, fauna (amphibians, reptiles, invertebrates, fish), ownership (if other than USFS), threats, and all names used by other researchers to describe the pond. All ponds are illustrated with photographs in Plates 1-8.

Number and dates of site visits varied for each pond. We use observations from these visits to describe the hydroperiod of each pond, where possible. Descriptors include 1) permanent; 2) rarely dry completely, but fluctuate; 3) dry infrequently; 4) highly ephemeral (usually fill each year, but have short hydroperiods); 5) rarely fill at all; and 6) changing (those whose hydroperiod may be changing over time).

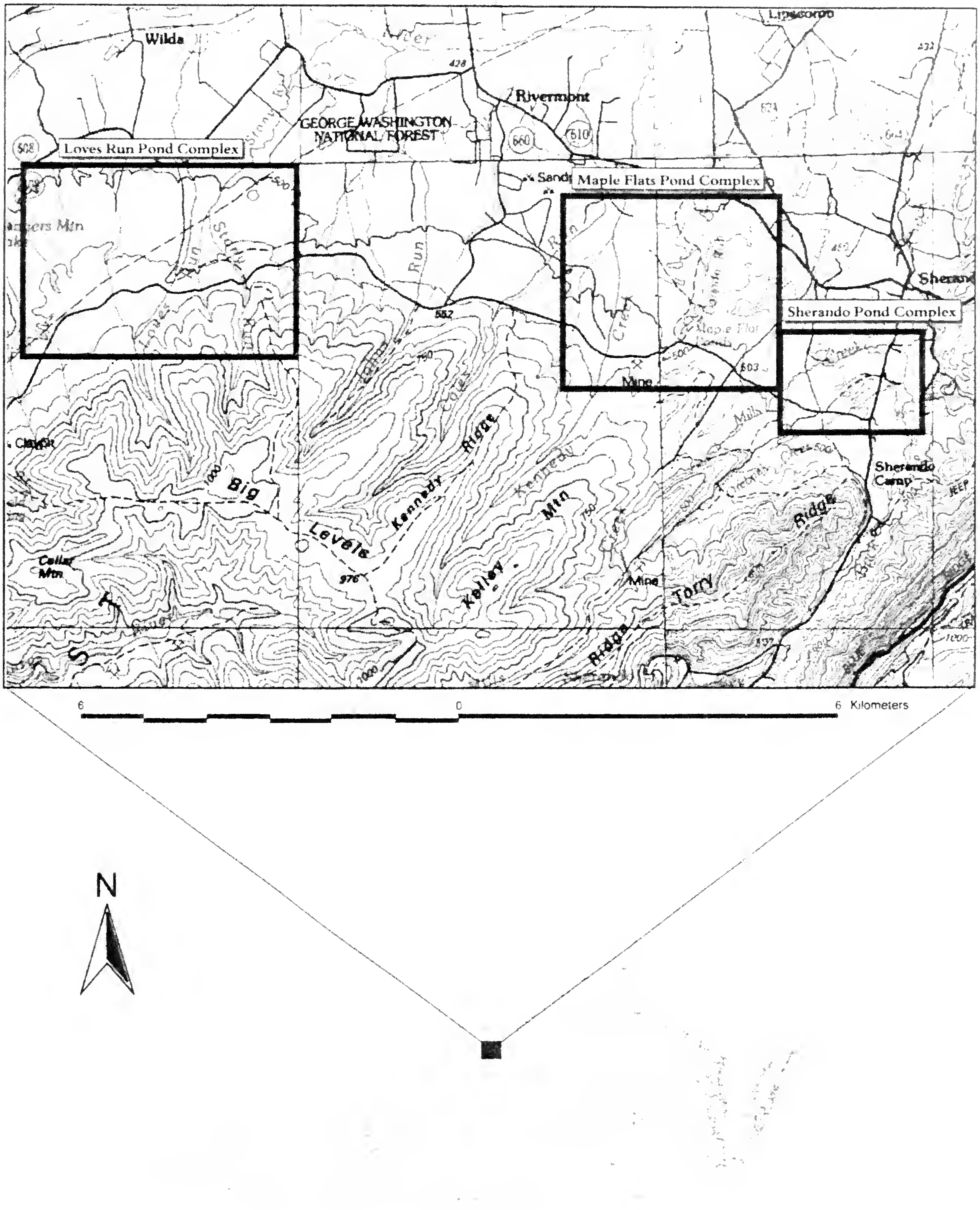


Fig. 1. Map depicting the three sinkhole pond complexes (Loves Run, Maple Flats, and Sherando) in the Shenandoah Valley Sinkhole Pond System, Augusta County, Virginia.

Maple Flats Pond Complex

The Maple Flats Pond Complex has been the focus of scientific investigations since the 1930s. Based on aerial photographs, forest habitat is known to have surrounded all of these ponds in September 1937 (Fig. 6c) when much of the surrounding Augusta County landscape was agricultural. Most of the ponds in this complex are located on U.S. Forest Service land, although significant ponds in private ownership are immediately adjacent to federal lands and are ecologically part of the complex (Fig. 1, 2, 6b). Most research and management discussions have focused on the Maple Flats complex. Twenty-two natural sinkhole ponds are described below. Two other man-made ponds also occur in the complex. We include them to provide a complete overview of the ponds in the complex and because they influence the fauna of the area.

Pond 1 (Plate 1)

Pond 1 is irregularly-shaped, measures approximately 30 x 34 m, and is 0.3 m deep when full. The pond is surrounded by an oak-hickory forest that provides a closed canopy. The bottom of Pond 1 has a decaying leaf substrate without *Sphagnum* or other aquatic vegetation. Pond 1 rarely fills and when it does, maintains water for short periods of time. It was observed filled in February 1994 and January 1998, and partially filled in March and July 1995 and February 1996. Pond 1 was dry (moist substrate) on 26 May 1987 when other ponds that rarely fill (see Ponds 3 and 14) contained some water. Successful metamorphosis of amphibian larvae from this pond has never been observed in any year from 1987-1998. Piles of dirt had been bulldozed into this pond sometime in the past and a large boulder blocks an access trail into the pond.

Pond 2 (Plate 1)

Pond 2 is oval-shaped, measures approximately 41 x 62 m, and is about 2.5-3.0 m deep when full. Trees surround the edge of the basin, but none are found within. Several large oak stumps occur within the pond near the edges. The pond has an open canopy. It is bordered to the east and south by an oak-hickory forest and to the north and west by a 1980 clearcut that was planted in white pine. When dry, the pond bottom is bare dirt and cobble with mats of *Sphagnum*, as well as some brush. When full, the surface is usually free of floating vegetation and the water is clear. A patch of grasses occurs inside the pond edge on the north side. Pond 2 is a highly ephemeral pond that sometimes fills in January (1992, 1998) or February (1994), but sometimes as early as October (1996) and occasionally not until March (1989). Pond 2 usually dries by June (1987, 1988, 1990, 1995). In July 1995, Pond 2 refilled completely after heavy rains, only to dry again by September of the same year.

The amphibian faunal assemblage consists of species that require seasonal ponds for breeding (Mitchell & Buhlmann, 1999). Annual juvenile recruitment is highly variable among species and among years and is directly related to hydroperiod. Depending on the time of filling and drying, dynamics among amphibian species vary among years (Mitchell & Buhlmann, 1999). For example, during dry autumns, female marbled salamanders (*Ambystoma opacum*) will deposit eggs under logs midway between the pond bottom and edge. The eggs hatch and larvae begin growing shortly after they are inundated by early-winter pond filling. Under these conditions, larval salamanders can attain a snout-vent-length (SVL) of 19-24 mm by March and are predators on the larvae of other later breeding amphibians. However, on 21 April 1989, the pond was overflowing after having been dry all winter. On this date, newly hatched marbled salamander larvae (SVL= 6-7 mm) and large aggregations of fairy shrimp (Order Eubranchiopoda) were observed. Fairy shrimp are among the most characteristic inhabitants of temporary ponds and pools (Pennak, 1978).

Pond 2 can be a "sink" habitat in some years for amphibians and a "source" habitat in others (e.g., Pulliam, 1988). By itself, Pond 2 could not maintain viable populations of the amphibian species in the area, but as part of a metapopulation of ponds, it is an important component in the Maple Flats Pond Complex. Another name for Pond 2 is Cold Pond (DNH files).

Pond 3 (Plate 1)

Pond 3 is nearly circular and measures approximately 46 x 52 m. It is relatively shallow and is less than 1.3 m deep when full. Although Pond 3 is surrounded by oak-hickory forest, it receives plenty of sunlight due to its size. The vegetation in the basin includes prairie willow (*Salix humilus* var. *tristis*), little blue stem (*Schizachyrium scoparium*), yellow wild-indigo (*Baptisia tinctoria*), and reindeer lichen (*Cladonia* sp.), all of which indicate infrequent filling. Other bottom substrate includes decaying leaves. One large pin oak (*Quercus palustris*) grows near the pond center and one shortleaf pine (*Pinus echinata*) grows inside near the edge; no other trees grow inside the basin. It has only been observed full with water two times (February 1994, March 1998) during the past 11 years. It was partially filled in May 1987, April 1994, and February 1995. It most often fills in winter and dries by early spring, but was observed with water in September 1996, possibly as a result of Hurricane Fran. Oddly, it was

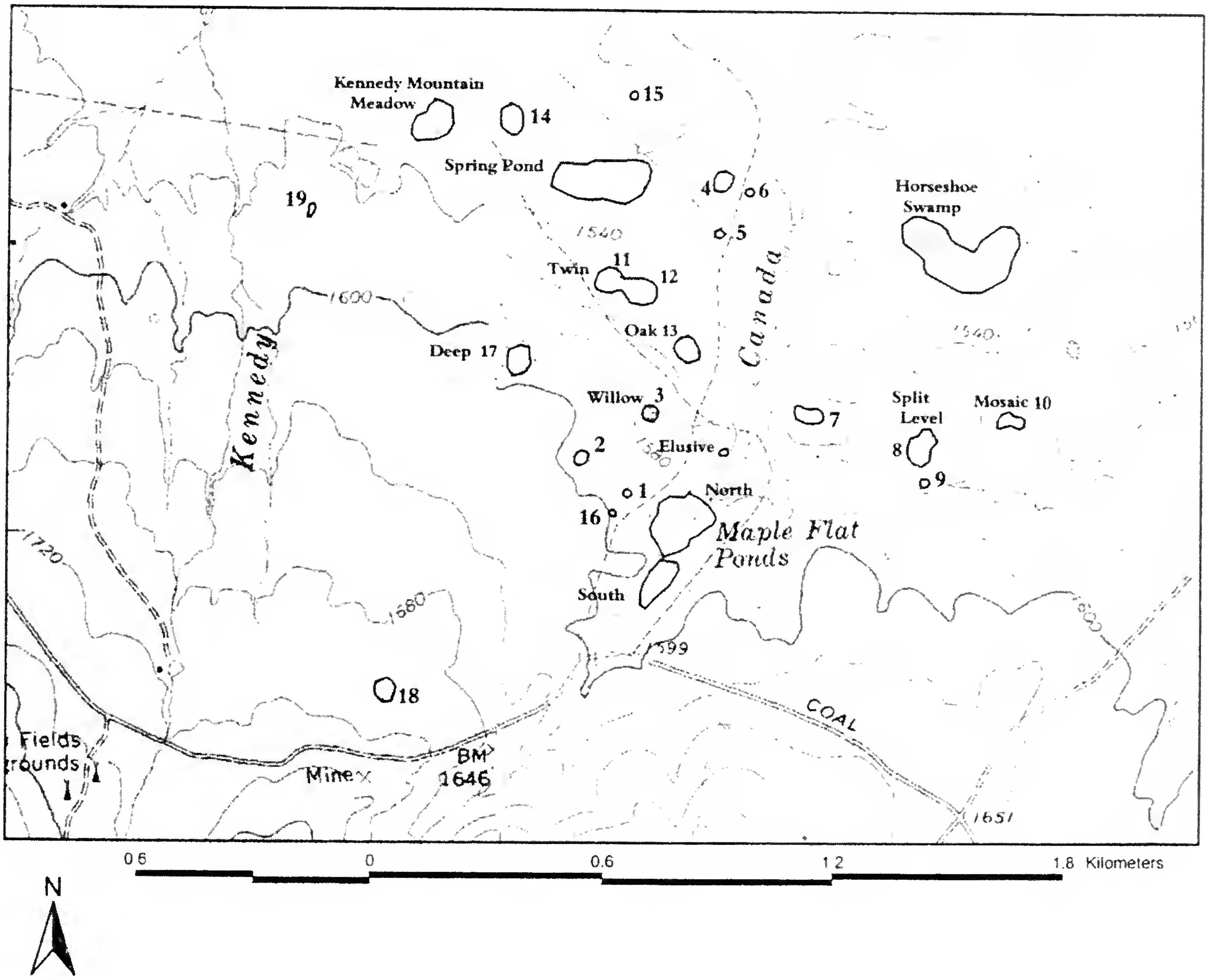


Figure 2. Maple Flats Pond Complex, Augusta County, Virginia. Each pond is numbered or named and those identifications correspond with descriptions given in the text.

completely dry on 21 April 1989 when nearby Pond 2 was overflowing.

The amphibian faunal assemblage consists of species that require seasonal ponds for breeding (Mitchell & Buhlmann, 1999). However, even in years when water was present, the hydroperiod was very short and salamander larvae (*Ambystoma* sp.) have never been observed to metamorphose successfully. Other names for Pond 3 include Dry Pond and Willow Pond (DNH files).

Pond 4 (Plate 1)

Pond 4 is oval-shaped and measures approximately 34 x 54 m. It is relatively shallow and is less than 1.2 m when full. Pond 4 is completely surrounded by a pin oak and black gum (*Nyssa sylvatica*) forest. *Sphagnum* grows throughout the pond and fallen trees are abundant in the basin. Greenbrier (*Smilax* sp.) grows around the pond edge. When the basin is full, accessing the pond edge is

difficult. Little information is available about the hydrology of Pond 4. It has been observed full on 23 March 1995 and low (0.3 deep) on 14 October 1987. The pond is on private property immediately adjacent to USFS land and has been slightly impacted by dirt bikes.

Pond 5 (Plate 1)

Pond 5 is irregularly-shaped and measures approximately 26 x 27 m. It is shallow and is 1.0 m deep when full. Pond 5 is located within a former clearcut (cut in 1980). When first visited in October 1987, it was dry and filled with brush and stumps and contained some dry *Sphagnum* and bottlebrush grass (*Elymus hystrix*). When revisited on 23 March 1995 the surrounding forest consisted of 15-year-old white pine and pin oak regeneration. Pond 5 was full March 1995 and January 1997, partially full during May 1995, and dry in October 1987 and May 1997. The nearest hardwood forest is 50 m distant. Pond 5 was full on 23 March 1995 and contained numerous salamander (*Ambystoma* spp.) egg masses. Numerous metamorphic green frogs (*Rana clamitans*) were present on 4 October 1987.

Pond 6 (Plate 2)

Pond 6 is small, circular, and measures approximately 21 x 24 m. It is shallow and is 0.6 m deep when full. Pond 6 is surrounded by a mixed oak forest, including white oak (*Q. alba*), pin oak, and chestnut oak (*Q. montana*). There is one pin oak growing near the pond center. Vegetation within the pond includes some grasses, *Sphagnum*, and decaying leaves. Pond 6 was full on 5 January 1997 and dry by 28 May 1997. It was also dry on 23 March 1995. It fills infrequently. No faunal information has been collected. Pond 6 is located on private property immediately adjacent to USFS land. Between visits in 1987 and 1995, it was impacted by off-road vehicles (see Plate 2).

Pond 7 (Plate 2)

Pond 7 resembles a wooded swamp, rather than a pond. It measures 74 x 98 m and appears to be very shallow. The basin consists of a complete and thick coverage of *Sphagnum*. It has a closed canopy. Trees and greenbrier grow throughout the basin. There are no defined pond edges. Pond 7 was dry when visited on 14 October 1987.

Pond 8 (Plate 2)

Pond 8 is a large pond that is generally elliptical with a narrow neck on the northeast side. It measures approximately 72 x 165 m. It is generally shallow and is 0.6 m deep when full. The pond is surrounded by an oak forest and has a completely open canopy. No trees grow within the large shallow basin. Pond 8 is the third largest pond in the Maple Flats complex; Spring Pond and Maple Flats Pond North are larger. The basin bottom is covered with grasses and *Sphagnum*. When full, Pond 8 is connected to Pond 9. Pond 8 was full in March 1995, but low in March 1988. Likewise, it was low in January 1992, but dry in January 1989. It contained water at least through May in 1988 and was recorded dry in September 1988 and October 1987. It was low in April 1989. Spotted salamanders (*A. maculatum*), spring peepers (*Pseudacris crucifer*), red-spotted newts (*Notophthalmus viridescens*), and snapping turtles (*Chelydra serpentina*) have been observed in Pond 8. Another name for Pond 8 is Split Level Pond (DNH files).

Pond 9 (Plate 2)

Pond 9 is a wooded swamp, approximately 27 x 32 m, and 0.6 m deep when full. It was connected to Pond 8 when water levels were high (March 1988 & March 1995) and contained some water in April 1989. It is completely shaded by surrounding forest and has a poorly defined pond edge. It contains some *Sphagnum*, but decaying leaves and brush dominate. Pond 9 is connected to Pond 10 by a small drainage. Five spotted salamander egg clusters were observed on 21 April 1989.

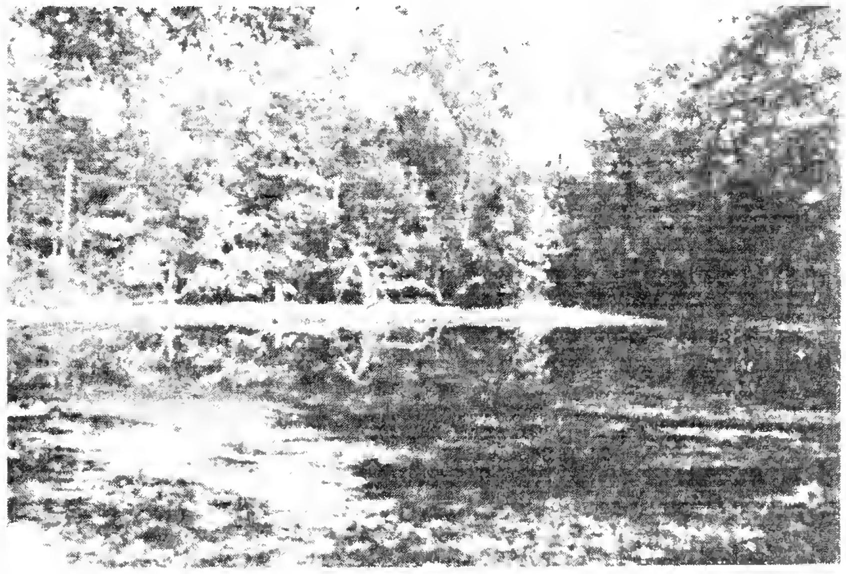
Pond 10 (Plate 3)

Pond 10 is approximately 35 x 72 m and is 0.6 m deep when full. It was full and thought to be relatively permanent when first visited in October 1987. Sedge clumps grew along the edges. *Sphagnum* was found throughout, and a moist grassy island was located in the pond center. The pond has an open canopy and is surrounded by mixed hardwood forest. However, Pond 10 was dry July 1988-February 1989. It was full on 21 April 1989, when spotted salamander egg clusters that appeared to have been eaten by turtles were found. Pond 10 was full in January 1992. When visited in March 1995, the drainage that flowed from Pond 10 had been impounded by beaver (*Castor canadensis*). The pond was flooded to a depth exceeding 2.0 m and the surrounding forest was flooded. A portion of the drainage towards Pond 9 was also flooded. In its current state, the habitat may not be suitable for several species of amphibians and reptiles that have been found there previously. Some turtles that were marked initially in Pond 10 in March 1988 were observed subsequently during April 1989, 2.5 km distant, in Pond 34 (Sherando

Pond 1. Photo taken 4 October 1987 from west pond edge looking east.

Pond 2. Photo taken 21 January 1988 from southeast pond edge looking northwest.

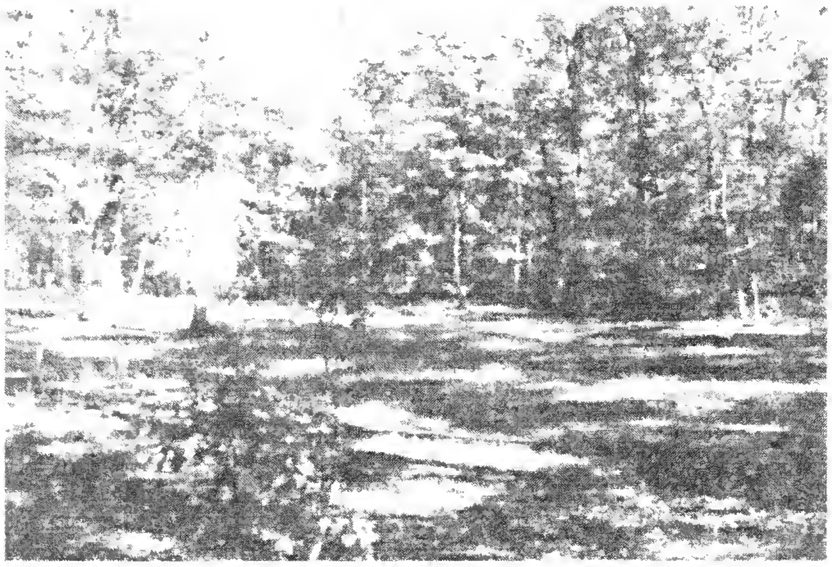
Pond 3. Photo taken 24 March 1995 from south pond edge looking north



Pond 4. Photo taken 4 October 1987 from west pond edge looking east.

Pond 5. Photo taken 4 October 1987 from southeast pond edge looking northwest.

Pond 5. Photo taken 24 March 1995 from southeast pond edge looking northwest.

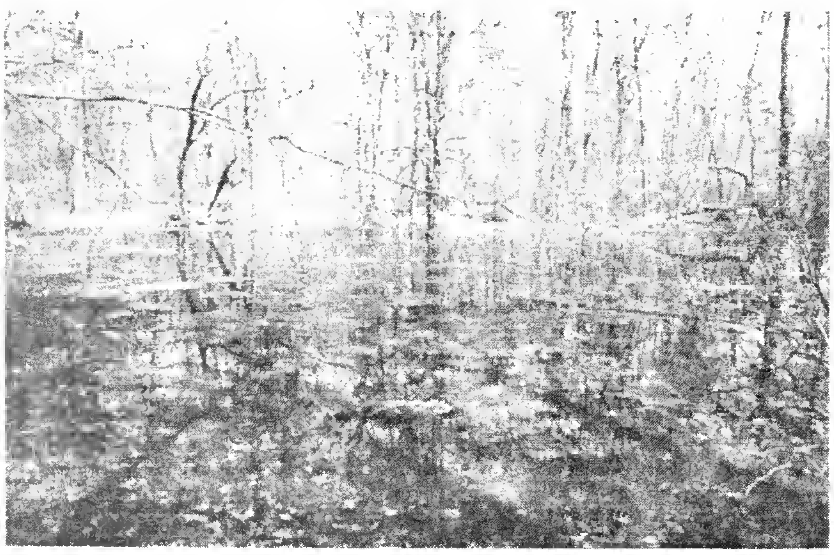


Pond 6. Photo taken 14 October 1987 from northwest pond edge looking southeast.

Pond 6. Photo taken 24 March 1995 from northwest pond edge looking southeast. Photo by JCM

Pond 7. Photo taken 14 October 1987 from north pond edge looking south.

Pond 8. Photo taken 18 January 1989 from southwest pond edge looking northeast.



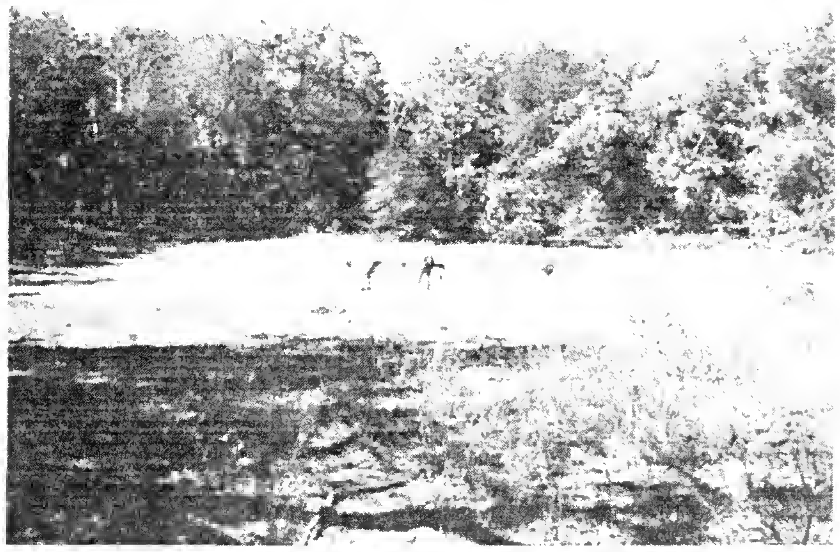
Pond 9. Photo taken 21 April 1989 from north pond edge looking south.

Horseshoe Swamp. Photo taken September 1998 by Gary Fleming.

Pond 10. Photo taken 18 January 1989 from northwest pond edge looking southeast.

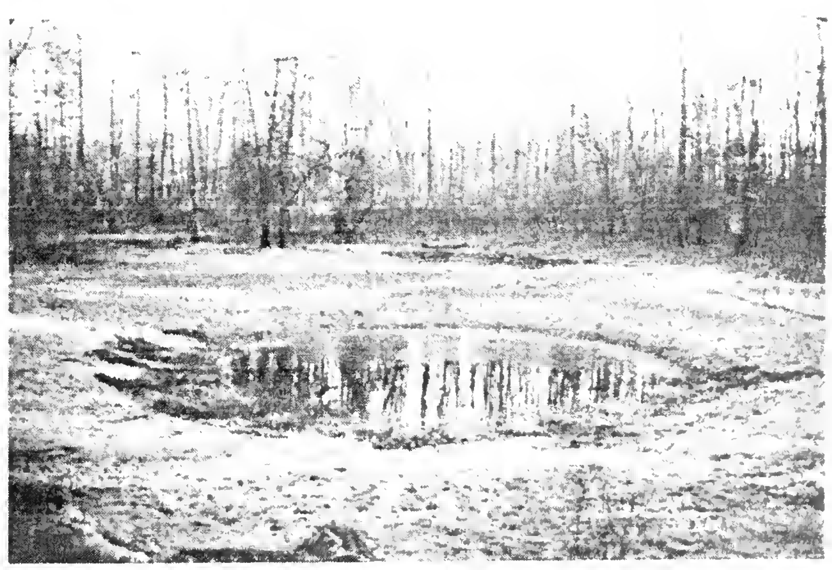
Pond 10. Photo taken 21 April 1989 from northwest pond edge looking southeast.

Pond 11. Photo taken 21 March 1988 from northwest pond edge looking southeast.



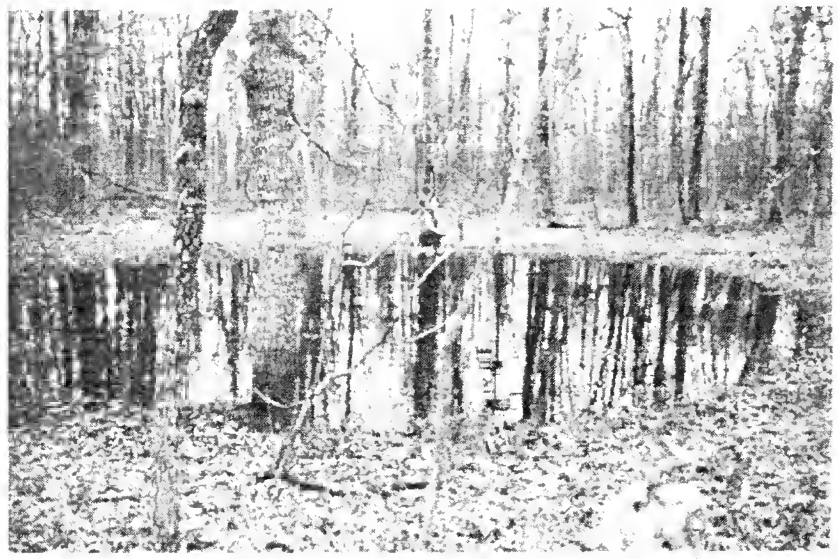
Pond 11. Photo taken 17 October 1998 from southeast pond edge looking northwest.

Pond 12. Photo taken January 1992 from northwest pond edge looking southeast.



Pond 13. Photo taken 18 January 1989 from west pond edge looking east.

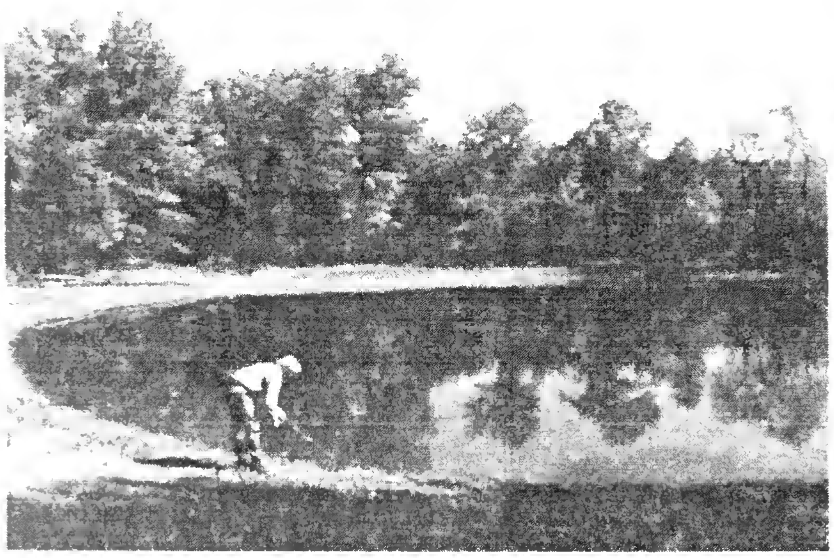
Pond 14. Photo taken 7 February 1992 from southeast pond edge looking northwest.



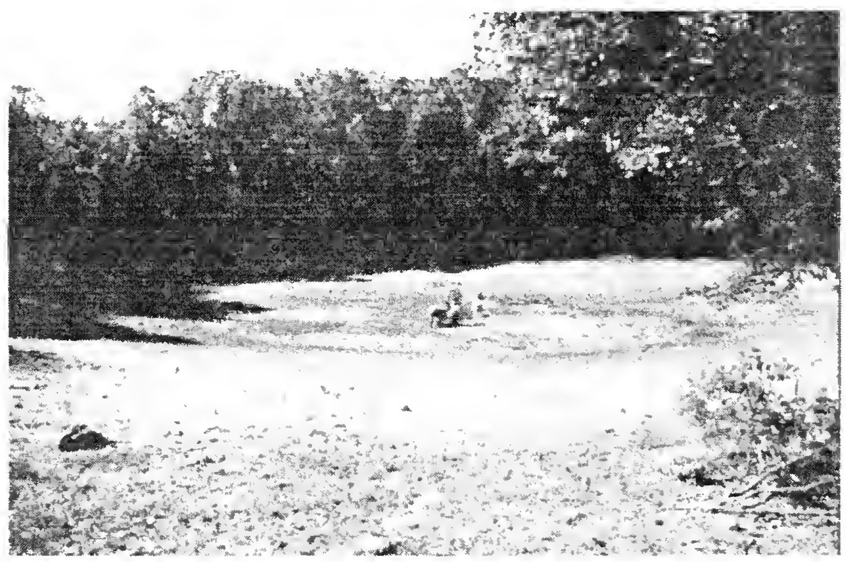
Pond 15. Photo taken 24 March 1995 from direction unknown.

Pond 16. Photo taken 4 October 1987 from west pond edge looking east.

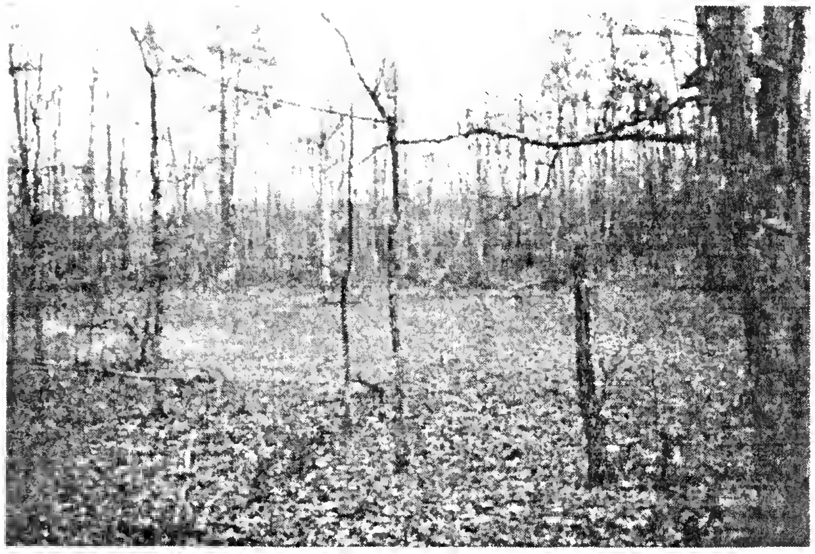
Pond 18. Photo taken 23 March 1995 from south pond edge looking north.



Pond 17. Photo taken 14 October 1987 from west pond edge looking east.
Photo by R. Glasgow.

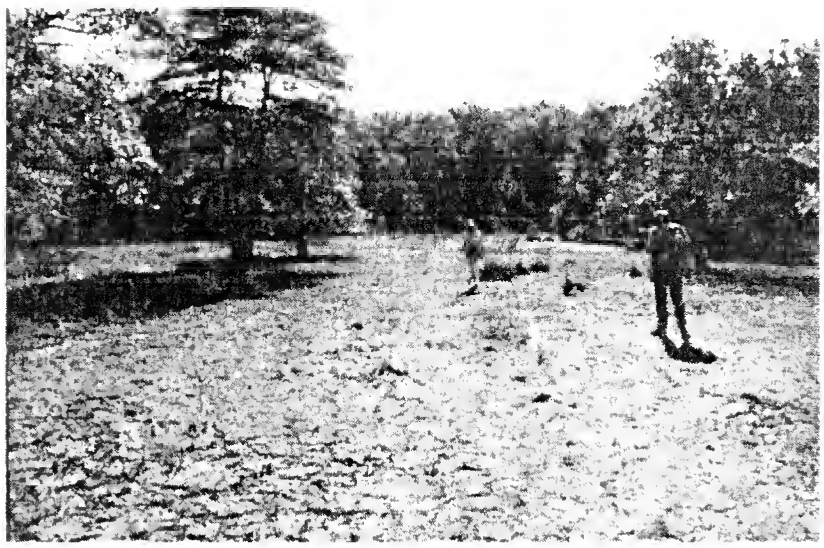


Pond 17. Photo taken 17 October 1998 from east pond edge looking west.



Pond 19. Photo taken 15 March 1988 from east pond edge looking west.

Elusive Pond. Photo taken 21 April 1989 from direction unknown.



Kennedy Mountain Meadow Pond. Photo taken 17 October 1998 from northeast pond edge looking southwest.

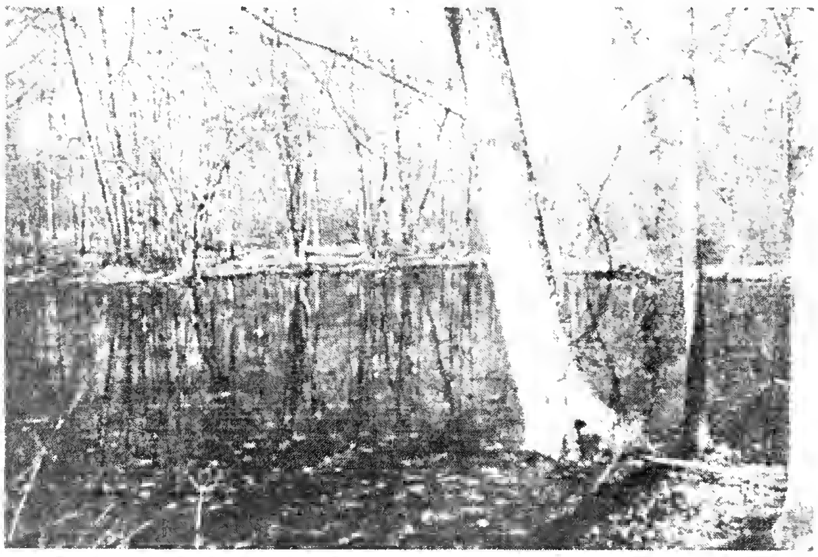
Spring Pond. Photo taken 26 May 1987 from south pond edge looking east.

Maple Flats North Pond. Photo taken 18 January 1989 from north pond edge looking southeast.

Maple Flats North Pond. Photo taken 17 October 1998 from north pond edge looking southeast. Photo by Don Church.

Pond 20. (aka Green or Quarles Pond)
Photo taken in August 1983 by Ali Wieboldt.

Pond 21. Photo taken 13 April 1988 from northeast pond edge looking southwest.

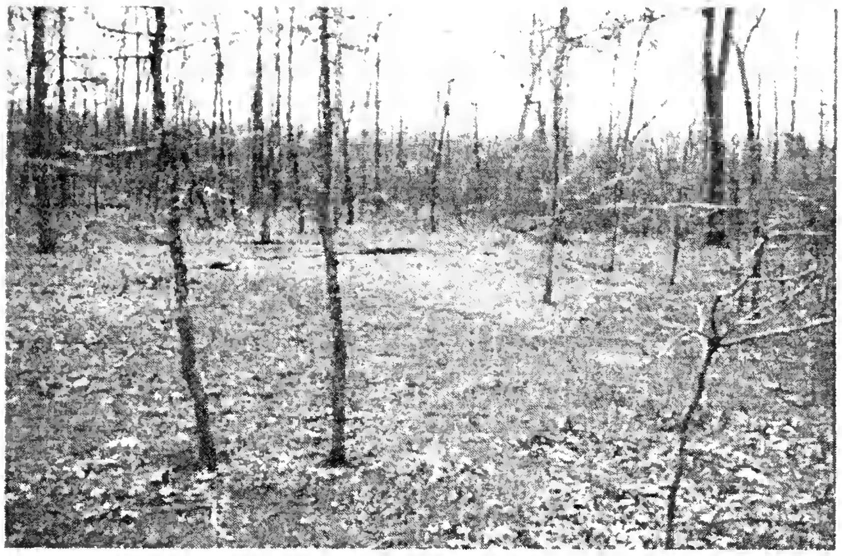


Pond 22. Photo taken 13 April 1988 from south pond edge looking north.

Pond 23. Photo taken 13 April 1988 from south pond edge looking north.

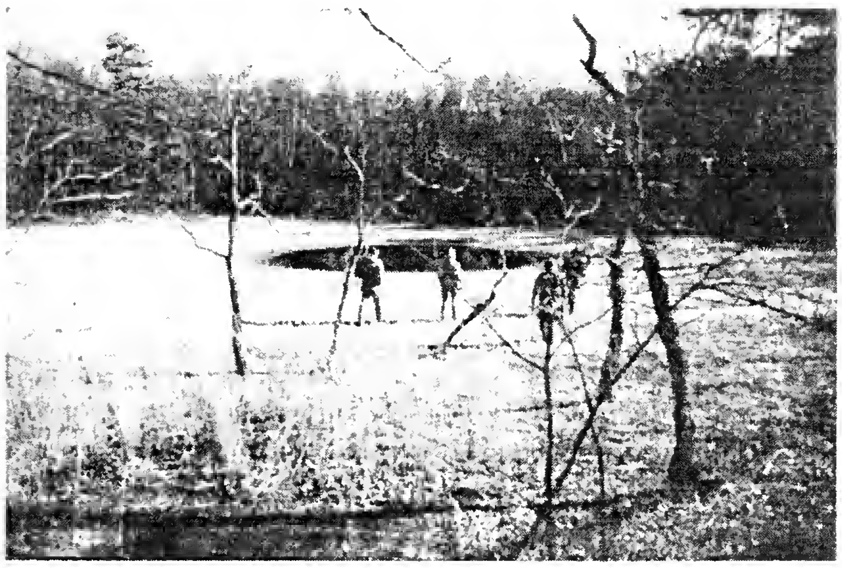
Pond 24. Photo taken 13 April 1988 from southwest pond edge looking northeast.

Pond 25. Photo taken 21 April 1989 from west pond edge looking east.



Pond 26. Photo taken 21 April 1989 from east pond edge looking west.

Pond 27. Photo taken 23 March 1995 from north pond edge looking south.



Pond 28. Photo taken 23 March 1995 from south pond edge looking north.

Pond 29. Photo taken 27 April 1988 from north pond edge looking south.

Pond 30. Photo taken 1 May 1988 from direction unknown.

Pond 31. Photo taken 1 May 1988 from direction unknown.

The gas right-of-way that separates ponds of the Loves Run complex. 21 April 1989.

Pond 32. Photo taken 21 April 1989 from east pond edge looking west.

Pond 33. Photo taken 21 April 1989 from northeast pond edge looking southwest.

Pond 34. Photo taken 21 April 1989 from west pond edge looking east.

Pond 35. Photo taken 18 May 1988 from west pond edge looking east.

Pond 36. Photo taken 18 May 1988 from south pond edge looking north.

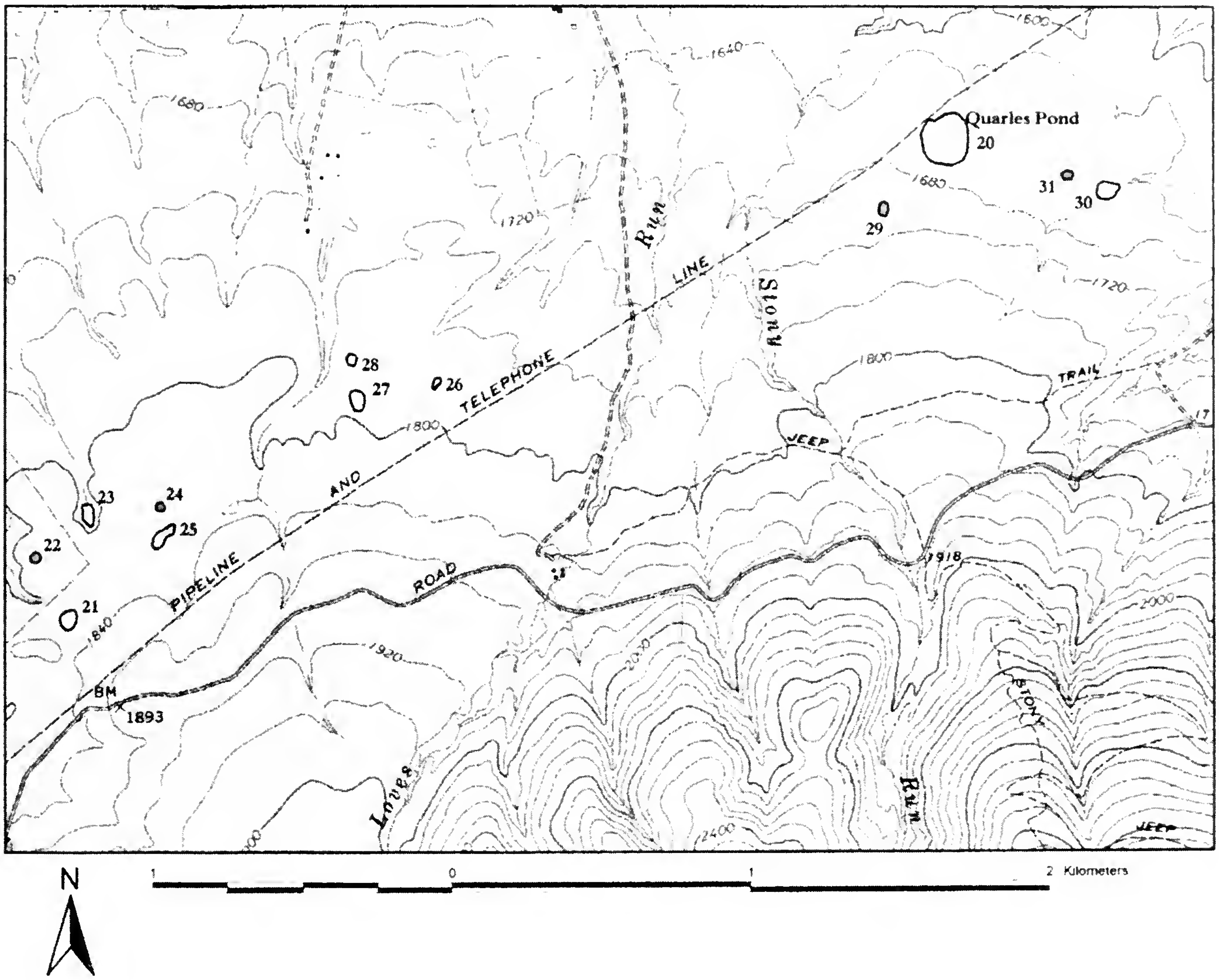


Fig. 3. Loves Run Pond Complex, Augusta County, Virginia. Each pond is numbered or named and those identifications correspond with descriptions given in the text.

Pond Complex) illustrating the need to consider conservation of the SVSP system in a metapopulation and landscape level context. Another name for Pond 10 is Mosaic Pond (DNH files).

Pond 11 (Plate 3)

Pond 11 is a circular depression approximately 53 x 66 m in size that is nearly 2.0 m deep when full. It is connected to Pond 12 when the pond is full. The two ponds together have often been referred to as Twin Pond(s). Pond 11 (Twin Pond North) is surrounded by hardwood forest but has an open canopy. No trees grow within the pond basin. This is a shallow pond with grasses growing in shallows and the rare endemic plant, Virginia sneezeweed (*Helenium virginicum*) occurring along the edges. *Sphagnum* mats are present in the deeper areas. Cobble-sized rocks are prominent on the bottom and the water is usually clear. Pond 11 dries completely only infrequently and has only been observed dry in October 1997 and 1998 since our study began in 1987. Depending on the year, Pond 11 has been observed full in most months. It has had its lowest water levels recorded in September (1992, 1994, 1997, 1998). Hundreds of dead *Rana* tadpoles were observed in a 1 m diameter depression at the pond's dry center on 17 October 1998. Although located on USFS land, 4-wheeler tracks were found in 1989. Those same ruts were still visible on the pond bottom in October 1998.

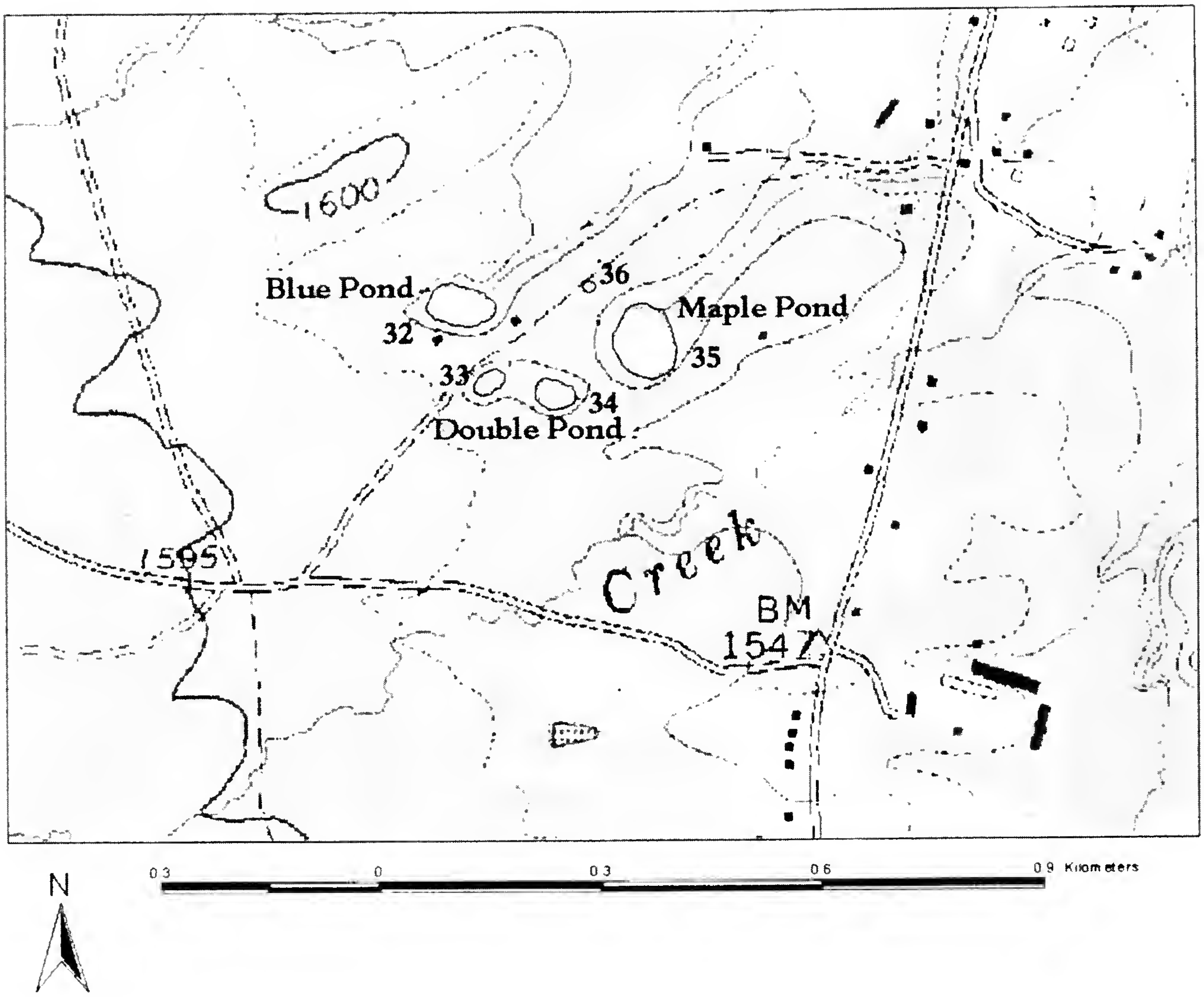


Fig. 4. Sherando Pond Complex, Augusta County, Virginia. Each pond is numbered or named and those identifications correspond with descriptions given in the text.

Pond 12 (Plate 3)

Pond 12 is a circular depression approximately 60 x 76 m and is nearly 2.0 m deep when full. It is connected to Pond 11 when the water is at its highest and has been referred to as part of the Twin Pond(s). Pond 12 (Twin Pond South) is also partially surrounded by hardwood forest but has an open canopy. The east side of this pond borders a 15-year-old clearcut that consists of white pine and pin oak. This same clearcut extends to encompass Pond 5 (see Fig. 6a). No trees grow within the pond basin. Pond 12 is a shallow pond with rare Oakes pondweed (*Potomogeton oakesianus*) occurring throughout. Cobble-sized rocks are prominent on the bottom and the water is usually clear. Pond 12 dries completely only infrequently and has only been observed dry once during October 1997, since the study began in 1987. Its hydrologic cycle seemed similar to Pond 11, but it will hold water longer by a month or so. Pond 12 contained a 50-m diameter circle of water on 17 October 1998, when other ponds that dry infrequently had dried. On several occasions, red-spotted newts have been observed under logs in dry portions of the pond basin. On 16 October 1997, Pond 12 was pumped dry by the USFS to eliminate bluegill sunfish (*Lepomis macrochirus*) that had been stocked there.

Pond 13 (Plate 3)

Pond 13, often called Oak Pond, is nearly circular, measures approximately 66 m x 72 m, and is nearly 4.0 m deep when full. The pond is surrounded by an oak-hickory forest but has an open canopy in the pond center. Large

oaks surround the edge and provide partial shade on all sides. The pond has a gently sloping bottom, until it reaches the center, where there is a deep hole containing about 1 m of organic matter. The bottom of Pond 13 is covered with *Sphagnum* that often floats to the surface when the pond fills and forms large floating mats. Pond 13 fluctuates but rarely, if ever, dries completely. It has never been observed to dry completely during our study, as the center depression always retained some water. Pond 13 usually refills in either January or February. The lowest water levels have been recorded August -January. Pond 13 was near full on 21 April 1989, when Pond 2 was overflowing. Amphibian larvae have been able to metamorphose successfully from Pond 13 in all years of the study, 1987-1998. Pond 13 is probably one of the most important ponds for amphibian reproduction in the Maple Flats Pond Complex (Mitchell & Buhlmann, 1999). Frogs, such as green frogs (*Rana clamitans*) and bullfrogs (*R. catesbeiana*), that require permanent ponds can also reproduce successfully in Pond 13. Many species of odonates, giant water bugs, wood ducks, great blue and green-backed herons, and belted kingfishers have been observed.

Pond 14 (Plate 4)

Pond 14 is an elliptical pond measuring 24 x 27 m. It is < 1 m deep when full and contains little live vegetation. When full, the water is dark due to the decaying leaves in the bottom. It is partly shaded by pin oaks that grow around the edges. The surrounding habitat includes a 15-year-old clearcut planted in white pine. Pond 14 is highly seasonal and does not fill in all years. Its hydroperiod allows it to be classified behaviorally intermediate between Ponds 2 and 3. For example, it held water into June during 1987, long enough for larval salamanders to metamorphose, whereas Pond 3 dried too early in May. In February 1992, Pond 14 was partially filled, whereas Pond 3 was dry. In March 1995, the pond was partially filled; on all other visits it was dry. The pond is on USFS property but borders private land.

Pond 15 (Plate 4)

Pond 15 has been visited infrequently during this study. It is circular and measures 15 x 15 m, and is 0.6 m deep when filled. It is a small depression, surrounded by an oak forest. No vegetation other than decaying leaves was present on the clay substrate. It probably fills infrequently or has a short hydroperiod. It has been observed dry in October 1987 and partially filled in March 1995. Pond 15 is on private property adjacent USFS land and is near Spring Pond.

Pond 16 (Plate 4)

Pond 16 is a small, deep, conical pond measuring 13 x 18 m and exceeding 3.0 m in depth when full. No vegetation other than decaying leaves is present. Pond 16 is surrounded by an oak-hickory forest. The pond is most likely to be full January-March, but has been observed full in May 1992 and July 1995. It has been observed dry June-September, but begins to refill in October in some years. Recently, a large oak tree that had been growing on the inside of the sinkhole rim toppled across the basin, leading to speculation that the sinkhole might be expanding. Pond 16 was partially filled with water during Spring 1988 and never completely dried that year. On 21 June 1988, marbled salamander larvae were still present in Pond 16, although larvae of the same species had metamorphosed and left the dry basin of adjacent Pond 2. Cricket frogs (*Acris crepitans*), amphipods, and diatoms are often numerous. Bullfrogs and green frogs are often seen here. Pond 16 is also called Conical Pond (DNH files).

Pond 17 (Plate 4)

Pond 17 is a large, circular pond measuring 61 x 75 m. It is 3.0 m deep when full. The pond is bordered by a 15 year old white pine plantation on the south side and oak-hickory forest on the other three sides. The pond basin is open, and the shallower areas are covered with grasses, whereas the deepest portion of the bottom is covered with algae. The deepest section also contains a spikerush, *Eleocharis acicularis*, that is prominent when the pond is dry. It does not dry every year and its hydroperiod seems similar to Ponds 11 and 12. However, in January 1992, Pond 17, which is up slope from Ponds 11 and 12, was observed completely full when those ponds were nearly dry. The water in Pond 17 is usually very clear during winter visits, however, it was unexplainably turbid in January 1997. The pond has been observed full in the winter and spring months of most years. Even in drought years, the pond only dries in the latter part of the summer. On 12 August 1988, a small circle of water 5 m in diameter remained, but by 7 September 1988 the pond was dry. The pond was dry on 17 October 1998. Pond 17 is used by amphibians such as *Ambystoma* spp. and wood frogs (*Rana sylvatica*). The long hydroperiod of Pond 17 suggests that it is a relatively reliable source pond for recruiting metamorphosing amphibians into the adult population. Green frogs and red-spotted newts are also common. The white pine plantation that separates Pond 17 from Pond 2 may have been a barrier to amphibian dispersal when it was a clearcut, and it may still be. The effects on amphibian movements of such habitats should

be evaluated. Pond 17 has been called Deep Pond (DNH files) and Clear Pond (Buhlmann & Mitchell, 1988).

Pond 18 (Plate 4)

Pond 18 is a small wooded pond with poorly defined edges that is shaded under an oak canopy. Maximum depth is 0.8 m when full. Abundant *Sphagnum* carpets the pond bottom. It is surrounded by an oak-hickory forest. Very little is known about the hydrology of Pond 18. When visited in March 1988, the pond contained water and several salamander (*Ambystoma* spp.) and wood frog egg masses were observed. It also contained some water on 23 March 1995 when more than 90 spotted salamander egg clusters were counted. Green frogs, red-spotted newts, and four-toed salamanders (*Hemidactylium scutatum*) were observed on 6 July 1998 when the pond was partially filled.

Pond 19 (Plate 5)

Pond 19 is a small shallow, elliptically-shaped pond, with a clay bottom devoid of *Sphagnum*. It was dry during visits on 15 March and 13 April 1988 and is probably < 0.6 m deep when full. A very wet spring would be needed for the pond to hold water long enough for amphibian larvae to successfully develop. In 1988, Pond 19 was proposed to be impacted by timber activities in Cut Unit 1119-2. It has not been revisited since Spring 1988, and its current condition is unknown.

Elusive Pond (Plate 5)

Elusive Pond in an irregularly-shaped, closed canopy depression. It is small and lies between Pond 13 and the man-made Maple Flats North pond. It has shrubs around the edges and a bottom covered with dead leaves. It was clear, full, and 1.0 m deep when visited on 21 April 1989. Nine spotted salamander egg clusters were observed on that date.

Horseshoe Swamp (Plate 2)

Horseshoe Swamp is a diverse wetland complex that occurs in a 10-acre, spring-fed, shallow depression that drains by a single outlet to Canada Run. It consists mostly of red maple-pitch pine dominated, seasonally-flooded swamp forest, but also includes shrub swamp and emergent wetland communities. Two open, marshy areas of approximately 1.5 acres and 0.2 acres are present. Groundwater flows into the wetland in high volumes during the winter months, but water is mostly absent in the summer and early fall. Water levels in the ponded areas range up to 1.0 m deep. The forested wetlands have a shrub layer of highbush blueberry (*Vaccinium corymbosum*), maleberry (*Lyonia ligustrina*), and swamp azalea (*Rhododendron viscosum*). *Sphagnum* occurs throughout. A portion of the community is saturated or inundated to such duration that the tree canopy thins and a shrub swamp forms, dominated by the heaths listed above. The lowest portions of Horseshoe Swamp consist of a seasonally and semi-permanently flooded herbaceous community dominated by emergent species such as Barrett's sedge (*Carex barrattii*), three-way sedge (*Dulchium arundinaceum*), Canada mannagrass (*Glyceria canadensis*), sharp-scaled mannagrass (*Glyceria acutiflora*), mild water-pepper (*Polygonum hydropiperoides*), Canada rush (*Juncus canadensis*), and buttonbush (*Cephalanthus occidentalis*). To date, only botanical investigations have been conducted; a faunal survey is needed.

Kennedy Mountain Meadows (Plate 5)

Kennedy Mountain Meadows is a large shallow pond (see Fig. 2). Carr (1937-38) described this pond as a shallow basin in the heart of the flatwoods of the Blue Ridge. The pond basin is < 1 m deep when full, pond edges are poorly defined, and small oak trees grow throughout the pond. The canopy is relatively open and the pond has a savanna-like appearance when dry. *Sphagnum* is abundant. The pond is partially surrounded by a mixed oak and pine forest and by a young stand of planted pines. The pond is on private property adjacent to Pond 14 and near Spring Pond. On 3 March 1988 it contained some water; on 21 March 1988 the depth was < 0.3 m and we counted salamander (*Ambystoma* spp.) egg clusters. On that date no marbled salamander larvae were seen, but freshwater shrimp and diatoms were collected.

When the pond was dipnetted again on 17 May 1988, no larval salamanders were found, suggesting that the pond may have dried and refilled since the previous March visit. It was dry in January 1992 and October 1998, and contained some water in March 1995. The Nature Conservancy continues to work with the landowner on the conservation of this site. An old ditch traverses the pond basin. Its effect on the hydrology is unknown. Knox (1997, 1999) studied Virginia sneezeweed (*H. virginicum*) in this pond for more than 12 years.

Spring Pond (Plate 5)

Spring Pond is one of the few permanent ponds within the Maple Flats Pond Complex. Spring Pond is a kidney-shaped depression that measures 92 x 226 m. It is approximately 1.0 m deep but has a soft, deep organic substrate. *Sphagnum* is restricted to the edges. No trees grow

Figure 5. Fragmentation of the landscape in the Sherando area of Augusta County, Virginia (circa 1979). The Maple Flats Pond Complex appears in the bottom third of the photograph. Fragmentation of the landscape and degradation of other sinkholes north of Maple Flats are evident. The Maple Flats Pond Complex represents only a remaining fraction of a once much larger complex of ponds.

in the pond basin. Golden club (*Orontium aquaticum*) covers the surface of the pond. The pond edges contain various shrubs, the rare swamp pink (*Helonias bullata*), and large-fruited cranberry (*Vaccinium macrocarpon*). Spring Pond is surrounded by hardwood forest. A small wildlife clearing is maintained adjacent to the south side of the pond.

Spring Pond maintains a relatively constant water level and is believed to be spring-fed. On 17 October 1998, the pond water level was down by 0.5 m. Spring Pond contains populations of bluegill sunfish and killifish (*Fundulus affinis*). Amphibians that prefer seasonal ponds for breeding sites, such as *Ambystoma* have not been recorded at Spring Pond. Spring Pond is the only known location for the spring salamander (*Gyrinophilus porphyriticus*) within the sinkhole pond complex and may also represent the source population for painted turtles (*Chrysemys picta*) that periodically appear in the seasonal sinkhole ponds (Mitchell & Buhlmann, 1999). Spring Pond has been referenced numerous times in the literature, and its unusual plant community was noted as early as the 1930s (Carr, 1938; Rawlinson & Carr, 1937). Spring Pond has also been called Hack Pond (Craig, 1969). Pitcher plants have been introduced here.

Maple Flats North Pond (Plate 5)

The Maple Flats North Pond is located adjacent to Canada Run in the Maple Flats Pond Complex. It is a manmade impoundment created in the 1950s for waterfowl management. The pond receives full sunlight and is approximately 135 x 150 m and 1-2 m deep when full. The water level can be controlled by a dam. The pond was reduced to a 20 x 50 m area, less than 0.25 m deep, in October 1998. It was also observed low in September 1987 and was refilling in October 1987. Bluegill sunfish and *Rana* spp. tadpoles are abundant. Spotted salamander larvae were captured in May 1987. The pond appears to have botanical characteristics of some other seasonal ponds in the area (N. Van Alstine & A. Belden, pers. comm.). Small seasonal pond or bog habitats may have been present on the site prior to construction (Fig. 6c).

Maple Flats South Pond (no photo)

The Maple Flats South Pond is fed by Canada Run that traverses the east side of the Maple Flats area. It is a man-made impoundment that was created in the 1950s for waterfowl management. The pond recieves full sunlight. It is approximately 51 x 102 m and at least 2.0 m deep when full. The water level can be controlled by a dam and has always been full when visited. Populations of cricket frogs, green frogs, and red-spotted newts inhabit this pond. Bluegill sunfish and *Rana* tadpoles are abundant. It is the only potential source for invasion of non-indigenous fishes into the sinkhole ponds of the area.

LOVES RUN POND COMPLEX

The Loves Run Pond Complex is located approximately 7.0-11.5 km west of the Maple Flats Pond Complex (Fig. 3). Only one sinkhole pond, called Grassy Pond, and containing Virginia sneezeweed, occurs in the landscape between these two complexes (DNH files). The Loves Run complex includes 12 ponds (Ponds 20-31) and the greatest distance between the outermost ponds is approximately 4.5 km. This complex also includes the largest pond in the SVSP system. A gas pipeline right-of-way separates Ponds 21-28 from Pond 20 and Ponds 29-31 (see Plate 8). Less information is available about this complex than the Maple Flats Pond Complex because most recent field studies were conducted in the latter area. However, earlier botanical work (Carr 1937, 1938) recognized several of these ponds. The Loves Run Pond Complex should also include Shenandoah Acres, a botanically significant pond identified by Carr in the 1930s and visible on 1937 aerial photography, that has been converted to a swimming lake. It was not investigated during this study. Several other ponds are visible on the 1937 photography that appear slightly southwest of the currently defined Loves Run complex; their current status is unknown. The Loves Run Pond Complex was forested in 1937 and continues to be forested to the present.

Pond 20 (Plate 6)

Pond 20 (Quarles Pond, Quarles Lake, Green Pond) is the largest sinkhole pond in the entire SVSP study area. Although not measured, it appears to be slightly larger than the man-made Maple Flats North Pond when viewed on aerial photographs. It is a large circular pond and appears to contain water permanently. It has a soft bottom with deep organic matter. Carr (1938) referred to it as Green Pond and noted that it was strikingly different from other ponds in the region, due to its abundance of spatterdock (*Nymphaea lutea* ssp. *advena*). During visits on 18 March and 27 April 1988, many red-spotted newts, cricket frogs, and *Rana* spp. tadpoles were observed. No *Ambystoma* spp. were observed. Painted turtles are present. On 23 March 1995 the surface was covered with emergent macrophytes. It does not contain golden club, as does Spring Pond, but has patches of *Scirpus torreyi* (T. Wieboldt, pers. obs.). Pond 20 is located along the gas pipeline right-of-way adjacent to USFS land and is privately owned. In 1988, the owner considered stocking sport fish in the pond, but was not believed to have done

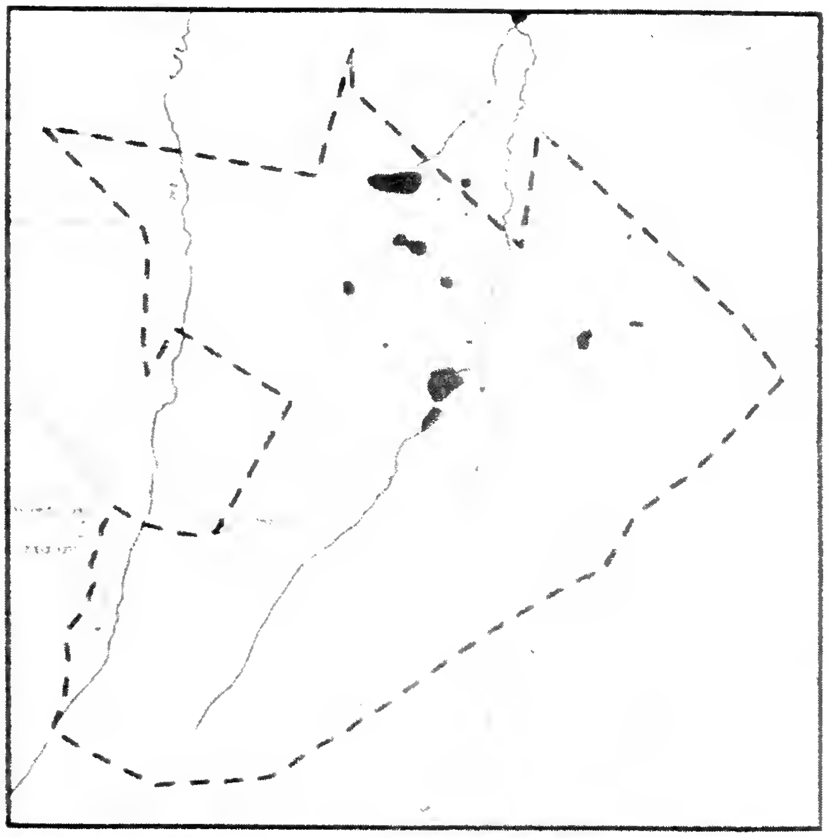


Fig. 6a.
Proposed boundary for the Maple Flats Research Natural Area.

Fig. 6b.
Maple Flats sinkhole pond complex, circa 1985.

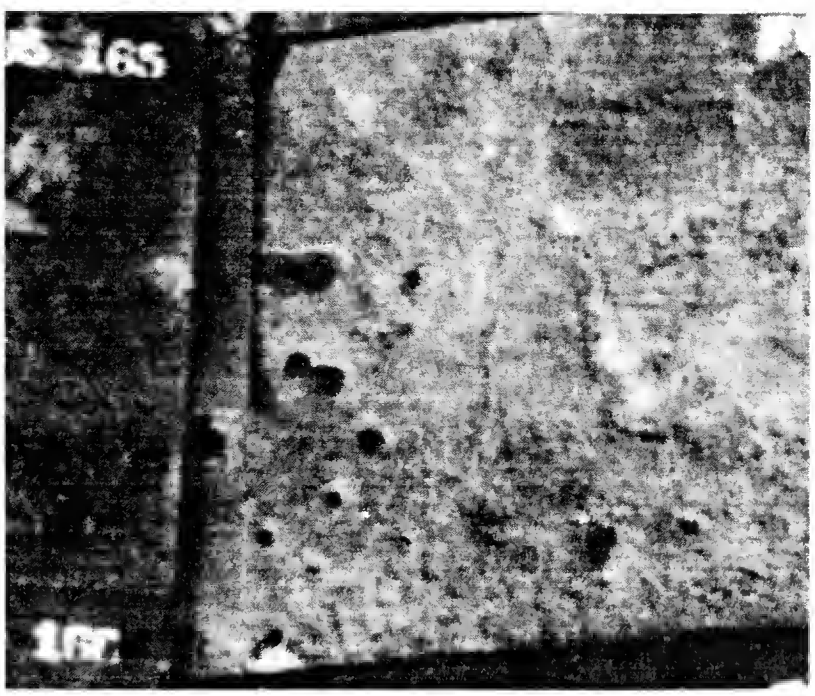


Fig. 6c.
Maple Flats sinkhole pond complex, September 1937.

Fig. 6. (a) Proposed boundaries for the Research Natural Area (RNA), (b) Aerial photograph of the Maple Flats Pond Complex, circa 1985, (c) Aerial photograph of the Maple Flats Pond Complex, September 1937.

so. He was also concerned about USFS plans to sell timber on the slope above the pond which could have impacted the pond via runoff.

Pond 21 (Plate 6)

Pond 21 is an elliptically-shaped, permanent pond. It is approximately 1.0 m deep but has a soft organic bottom that is at least 20 cm deep. Vegetation includes bladderwort (*Utricularia* sp.) and coontail (*Ceratophyllum* sp.). A mixed hardwood forest surrounds the pond. A steep embankment covered with *Rhododendron* borders the southern edge of the pond. The pond was full on 13 April 1988 when red-spotted newts and *Rana* spp. tadpoles were captured and painted turtles were observed basking. No *Ambystoma* larvae were dipnetted. The pond was also full on 21 April 1989 and 23 March 1995.

Pond 22 (Plate 6)

Pond 22 is a small, shallow pond with a leaf litter bottom. It contained some water on 13 April 1988. Pond 22 is located on private property and in 1988 was bordered by a clearcut on two sides. It may be a suitable *Ambystoma* breeding site in wet years.

Pond 23 (Plate 6)

Pond 23 is a small, elliptical, shallow (< 1 m deep), seasonal pond. A panic grass, *Panicum rigidulum*, grows throughout the firm-bottomed pond. A mixed hardwood forest surrounds the pond and the north side is edged with greenbrier. The pond contained some water on 13 April 1988, 21 April 1989, and 23 March 1995. Red-spotted newts, wood frog eggs, marbled salamander larvae, spring peepers and cricket frogs were found on the latter date. Marbled salamander larvae were also found on 21 April 1989.

Pond 24 (Plate 6)

Pond 24 is a shallow swale with grasses and *Sphagnum*. It is connected to Pond 25 when water levels are high. It is surrounded by hardwood forest. It contained some water on 13 April 1988 when red-spotted newts, marbled salamander larvae, and cricket frogs were captured. It contained water on 23 March 1995, but no vertebrates were observed.

Pond 25 (Plate 6)

Pond 25 is a large, shallow pond surrounded by hardwood forest. The pond edge is surrounded by greenbrier and *Sphagnum*. Pond 25 was full on 13 April 1988. It was also full on 21 April 1989 when red-spotted newts were observed. Pond 25 is similar in vegetative structure to Ponds 10, 33, and 34. *Ambystoma* sp. larvae, red-spotted newts, and spring peepers were observed here on 23 March 1995.

Pond 26 (Plate 7)

Pond 26 is a small, shallow depression. It probably holds water only in exceptionally wet years. It was dry on 13 April 1988 when we captured a northern water snake (*Nerodia sipedon*) under a log at the pond's center. The pond was also dry on 21 April 1989 and 23 March 1995. Pond 26 is shown to be full in a 10 March 1985 aerial photograph.

Pond 27 (Plate 7)

Pond 27 is a large circular pond that is several (> 3.0) meters deep when full. The pond is surrounded by an oak-dominated hardwood forest. The pond basin is covered with panic grass with the exception of a 30 m diameter circle of spikerush (*E. acicularis*) at the pond center. The pond was dry on 13 April 1988 and 21 April 1989. On 23 March 1995, the pond contained water in the center circle, at a depth of 0.5 m. Red-spotted newts were observed mating, wood frog egg clusters were present, marbled salamander larvae were observed eating the wood frog eggs, and spring peepers were calling. Red-backed salamanders (*Plethodon cinereus*) were observed under logs within the pond margin. Pond 27 was full on 10 March 1985 and dry on 16 March 1979 based on aerial photographs. Based on vegetation within the basin, Pond 27 appears not to have filled completely in many years. We categorize Pond 27 as filling infrequently; however, perhaps the underlying geology or hydrology has changed and the pond basin has lost its water resistant lining. Quarry activity in the region may be a concern.

Pond 28 (Plate 7)

Pond 28 is a large circular pond near Pond 27. It is 1.0 m deep when full, but fills infrequently. The pond is surrounded by an oak-dominated hardwood forest. The pond basin is covered with panic grass (*P. rigidulum*). The pond has always been dry when visited (13 April 1988, 21 April 1989, and 23 March 1995). Aerial photos indicate that it was dry on 16 March 1979 and full on 10 March 1985. There have been no sampling efforts to determine faunal composition.

Pond 29 (Plate 7)

Pond 29 is a large pond, similar in size to Pond 27, and was completely dry when visited on 27 April 1988. Sapling Virginia pine (*Pinus virginiana*) was invading the basin and downed woody debris (logs) was present. Aerial photos from 10 March 1985 show Pond 29 empty when all other nearby ponds (Ponds 27, 28) that fill very infrequently were full of water. Perhaps the water-resistant lining has been broken due to the dissolution of the limestone underneath. Geological and hydrological investigations are needed. On 27 April 1988, numerous red-spotted newts (red eft stage) and red-backed salamanders were found under log debris in the pond basin. Many slimy salamanders (*Plethodon cylindraceus*) were found under rocks along the inside edges of the pond basin. On 23 March 1995 there was no free water in the pond, but the center was moist and a young pin oak was growing in the center of the pond.

Pond 30 (Plate 7)

Pond 30 is a shallow pond that is slightly smaller than Pond 29. It was dry when visited on 27 April 1988 and had been impacted by 4-wheelers. It was shown to contain water on a 10 March 1985 aerial photograph. Pond 30 has been called Grassy Pond (DNH files).

Pond 31 (Plate 7)

Pond 31 is a small shallow pond adjacent to Pond 30. It was dry when visited on 27 April 1988. It has also been impacted by 4-wheeler use. Aerial photographs from 10 March 1985 indicate some standing water.

SHERANDO POND COMPLEX

The Sherando Pond Complex lies approximately 2-3 km east of the Maple Flats Pond Complex (Fig. 1). Five ponds (Ponds 32-36) occur in this group (Fig. 4). They are all in private ownership, although the properties border USFS land. Hardwood forest surrounds these five ponds, in contrast to other remnant ponds in the Sherando vicinity which have been altered and surrounded by agriculture, since at least 1937. These ponds are important in the overall metapopulation conservation of the SVSP system. At least one rare amphibian species is believed to breed in at least one of the ponds. Turtles originally captured in Pond 10 in the Maple Flats Pond Complex, a distance of 2.5 km, have been observed in Pond 34. The ponds were visited by us with permission from the tenants.

Pond 32 (Plate 8)

Pond 32 is a large, very deep, circular pond, exceeding 6.0 m deep when full. It is surrounded by forest but has an open canopy. The bottom substrate is firm. Two private homes are on the pond's edge. The tenant informed us that Pond 32 nearly dries in some summers. On 18 May 1988 the pond was full and the water was clear enough to see the bottom. Marbled salamander larvae, *Rana* spp. tadpoles, red-spotted newts, northern water snakes, and various invertebrates were dipnetted. Painted turtles were seen. We were told that goldfish had been stocked in 1987, but all had died during low water conditions the subsequent year. On 21 April 1989 the pond was again full. Pickerel frogs (*Rana palustris*) were calling and trout had been reportedly stocked in the pond. Pond 32 was called Blue Pond by Carr (1937-38).

Ponds 33 and 34 (Plate 8)

These are shallow, somewhat irregular-shaped ponds, that are approximately 0.7 m deep with profuse growth of grasses and *Sphagnum*. They are connected when the water is high and both are east of a gravel road which leads to private homes on the property. On 18 May 1988, Pond 33 was dry and Pond 34 contained some water. Both ponds were full on 21 April 1989. Painted turtles and northern watersnakes were captured on 18 May 1988. Ponds 33 (west) and 34 (east) have been called Double Pond (C. E. Stevens, pers. comm.).

Pond 35 (Plate 8)

Pond 35 is a large shallow pond with a soft bottom and Carr (1938) classified it as a permanent pond. On 18 May 1988, we collected invertebrates, red-spotted newts, and green frogs. No *Ambystoma* larvae were found. On 21 April 1989 it was also full and many painted turtles were observed. Pond 35 was called Maple Pond by Carr (1938).

Pond 36 (Plate 8)

Pond 36 is a very small sinkhole that has been partially filled with trash. It contained some water on 18 May 1988, but was dry on 21 April 1989. No faunal information is available.

DISCUSSION

The Value of Isolated Wetlands to Biodiversity

Isolated depressional wetlands of varying sizes, hydrology, and geologic origin occur throughout the eastern United States. The importance of such isolated

wetlands to biodiversity has been overlooked in the past, but is becoming increasingly recognized (Dodd, 1992; Burke & Gibbons, 1995; Buhlmann, 1998; Semlitsch & Bodie, 1998; Semlitsch, 1998). Isolated wetlands have been called different names depending on the region and their perceived origins (Lide, 1997; Sharitz & Gibbons, 1982; Schalles et al., 1989). For example, Carolina bays dot the southeastern Coastal Plain landscape from Georgia north to Delaware, but are most abundant in the Carolinas (Sharitz & Gresham, 1998). A cluster of sinkhole ponds, known as the Grafton Ponds Complex, is found in the Virginia Coastal Plain in York County (Pettry et al., 1979; Bliley & Pettry, 1979; Sankey & Schwenneker, 1993). Woodland vernal pools are recognized as important and threatened habitats in the northeastern United States for amphibians (Stone, 1992; Klemens, 1993; Kenney, 1994; Madison, 1997).

The Shenandoah Valley sinkhole ponds are unusual due to their location within the Blue Ridge physiographic region and their geologic origins. Sinkholes are a prominent feature of karst landscapes, such as the Cumberland Plateau (Holsinger & Culver, 1988). However, karst sinkholes rarely hold water due to the solution of limestone. In fact, surface streams often disappear underground in karst landscapes. However, Shenandoah Valley sinkhole depressions often have impermeable bottoms, permitting water retention and, hence, the existence of the unique sinkhole ponds. Because of the isolated position of the Shenandoah Valley sinkhole ponds, relative to other isolated wetlands complexes described above, and because the ponds themselves date back at least to the Pleistocene (Hack, 1965), it is not surprising that the floral and faunal communities of the SVSP system are unique and contain disjunct populations and rare and endemic species (Carr, 1938; Fleming & Van Alstine, 1999; Knox, 1999; Mitchell & Buhlmann, 1999; Roble, 1999).

Variation in SVSP Hydrology

Within the SVSP system, variation in hydrology among ponds promotes unique faunal and floral communities. No two ponds in the system are identical. Variation in hydroperiods, which results in a range of permanent to highly ephemeral ponds, is the underlying reason for the collectively significant biodiversity, and why it is essential to protect the entire system. Each species of rare plant, vertebrate, and insect is known from only a few of the ponds (Fleming & Van Alstine, 1999; Mitchell & Buhlmann, 1999; Roble, 1999). However, nearly every pond contains an element record for a species of conservation interest (Virginia Division of Natural Heritage, unpubl. data).

Variation in amphibian faunal assemblages is directly related to hydroperiod (Semlitsch, 1987; Pechmann et al., 1989; Mitchell & Buhlmann, 1999). For example, bullfrogs require ponds that hold water continuously for more than one year in order for larval development to be completed. Wood frogs and ambystomatid salamanders, such as spotted, tiger, and marbled salamanders, require fish-free ponds that usually contain water from late autumn through early summer (Hopey & Petranka, 1994). Because of year to year variability in hydroperiod of individual ponds, it is the large number of ponds in each complex that maintains the viability of populations within the system. For example, at eight ponds monitored over a 6-year period, 1987-1992, amphibian metamorphosis was successful at four (1991) to seven (1987) ponds depending on the year and rainfall (K.A. Buhlmann & J.C. Mitchell, unpublished data). Therefore, in some years, some ponds, such as Pond 2, can be sink habitats (e.g., Pulliam, 1988; Pulliam & Danielson, 1991) in which no larvae are recruited to the adult population or larvae are forced to transform at smaller body sizes (Semlitsch, 1988a; Mitchell & Buhlmann, 1999). Other ponds, such as Pond 13, may be source populations because they successfully rear metamorphic adults every year, and perhaps produce excess individuals that can disperse and recolonize other sites. In theory, sink populations alone are not viable populations because over the long term, mortalities exceed recruitment (Pulliam, 1988). Identifying source and sink populations is critical in the design of effective landscape conservation models.

Metapopulations and Landscape-level Management

The diversity of pond types is responsible for the diversity of plants and animals in the SVSP system. It is the collective complex of ponds that make this area important, and it is in that context that we must focus landscape-level, metapopulation conservation and management efforts. Fragmentation of habitat can lead to local population extinction (Noss, 1987; Opdam, 1991). Therefore, connectivity of habitats among ponds becomes an important management consideration (Beier & Loe, 1992; Beier & Noss, 1998) due especially to the variation in suitability among years exhibited by different ponds. Dispersal movements, microhabitat requirements, and use of corridors in terrestrial habitats by amphibians and reptiles, as well as other organisms, has received increased research attention in recent years (Buhlmann et al., 1993; Buhlmann, 1998; Burke & Gibbons, 1995; Dodd, 1995; 1996; Semlitsch, 1981; 1983a). Adult amphibians may move greater than 1 km away from wetland breeding sites (Williams, 1973; Dodd, 1996), and mean distances for pond-breeding salamanders was

estimated at 164 m for 95% of the population (Semlitsch, 1998). For nearly all amphibians and reptiles, the terrestrial habitat adjacent to aquatic breeding sites is equally as important as the ponds. Both habitats are required for populations of these species to exist (Bennett et al., 1970; Burke & Gibbons, 1995; Buhlmann, 1998; Dodd & Cade, 1998). From an amphibian perspective, terrestrial habitats that protect individuals from desiccation and freezing, and that provide suitable soil structure required for a fossorial existence (e.g., Semlitsch, 1983b) are essential. Therefore, before activities such as clearcutting are conducted, efforts should be made to protect appropriate terrestrial habitat surrounding ponds and maintain corridors between ponds and pond complexes. No timber operations should be conducted within 200 m of pond borders. Such activities have detrimental effects on the population dynamics of amphibian populations (deMaynadier & Hunter, 1995; Means et al., 1996; Palis, 1997; Petranka et al., 1993).

Other Threats to the SVSP System

The larger landscape perspective needs to be considered when designing long term conservation and management plans for the SVSP complex. Some ponds have already been lost due to agriculture, increasing human population size and associated new housing developments, filling, or conversion to swimming lakes. Some ponds have been impacted by off-road vehicle (ORV) users. Some ponds have been stocked periodically with game fish that negatively affect the breeding success of native amphibians (Semlitsch, 1988b) and likely alter trophic dynamics (e.g., Taylor et al., 1988). Ponds have been left isolated in the fragmented landscape throughout the Sherando area north of the pond complexes addressed in this paper (Fig. 5).

The SVSP system lies in the region of the Appalachians that receives acid precipitation in the form of sulfuric and nitric acid from prevailing westerly winds (Galloway et al., 1983; Hyer et al., 1995). Acid levels in streams in the Blue Ridge and Ridge and Valley physiographic provinces in Virginia have increased over the past several decades and atmospheric pH values of 4 or less are not uncommon (Webb et al., 1989; Camuto, 1991). Acid-base chemistry studies of some of the ponds in the SVSP system (Downey et al., 1999) reveal that nearly all of the sinkhole ponds are acidic and that some exhibit pH readings low enough to be potentially harmful to plants and animals. Two-year average pH values for 28 ponds range from 4.74 to 6.0 and corresponding acid neutralizing capacity levels range from -30.4 to 22.2, indicating no neutralizing capacity in the system (Downey et al., 1999). In addition, acidity can increase quickly to about pH 4.0 during some rain events in some ponds. High acid levels are known to be detrimental to amphibians and invertebrates by reducing embryo and larval survival, and affecting behavior (Dunson & Connell, 1982; Freda, 1986; Freda & Dunson, 1986; Freda & Taylor, 1992; Kutka, 1994). Risk from anthropogenic pollution should be assessed for at least all rare and listed species in the SVSP system, based on current knowledge about acid conditions.

Conservation of the Shenandoah Valley Sinkhole Pond System

The Loves Run Pond Complex has been designated as a Special Interest Area by the USFS. The Maple Flats Pond Complex, located largely on U.S. Forest Service property and encompassing 272.8 hectares (Smith, 1991), may be designated as a Research Natural Area (Fig. 6a). An adjacent pond on private property, Kennedy Mountain Meadows, has been under conservation agreement between the landowner and The Nature Conservancy. However, despite these encouraging efforts, the focus of conservation needs to be expanded. Cooperative conservation agreements should be initiated with owners of ponds on all adjacent private lands. All isolated wetlands, no matter how small, are important for maintaining biodiversity across the landscape (Semlitsch & Bodie, 1998). Management strategies should not be limited to the ponds themselves, but also include appropriate terrestrial buffer habitats and provide corridors and landscape linkages to other ponds and pond complexes.

The Shenandoah Valley Sinkhole Pond system represents a wealth of biodiversity that is part of the natural heritage of the Commonwealth of Virginia and the Appalachian region. Progressive management, protection, and conservation efforts must be pursued jointly among federal and private landowners, and state and local governmental agencies to ensure that the legacy of the area is preserved for future generations and to prevent significant biodiversity losses.

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Water Chemistry Assessment of The Shenandoah Valley Sinkhole Ponds in Virginia

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INTRODUCTION

Low solubility, siliciclastic rocks of the Antietam Formation make up the underlying geology of the mountains and ridges of the Big Levels region in the Blue Ridge Physiographic Province of the Shenandoah Valley of Virginia (Werner, 1966; Bartholomew, 1977). Alluvial deposits of this rock lie over top of dolomitic limestone formations at the base of the mountains, creating a fan up to five kilometers wide and thirty meters deep (Hewitt et al., 1917; Whittecar & Duffy, 1992). The sinkhole ponds found in this region were created by the collapse of pockets in this limestone. The alluvium is covered by thin soils of medium water retention and moderate permeability of the Monogahelia and Sherando sandy loam types (Hockman, 1979). Although the hydrology of the fan has not been studied extensively, it is apparent that the ponds fill by water travelling down from the upper elevations through the alluvium and acidic soils. Few of the ponds are stream fed or fill fully by surface water runoff alone. Some maintain constant pool levels during dry seasons due to springs within the basins, while others rise and fall dramatically in pool depth (Buhlmann et al., 1999). Many ponds dry completely on an annual basis.

Headwater streams that originate from catchment basins with low solubility siliciclastic bedrock geology are particularly susceptible to acid rain impacts due to low carbonate buffer availability (Bricker & Rice, 1989). Rainfall in western Virginia averages pH 4.3 to 4.5 (NADP database), or between one-half and one pH unit lower than pre-industrial age precipitation (Drever, 1988; Schindler, 1988). In most surface waters, carbonate provided by minerals such as calcite neutralizes most of the anthropogenic acidity. However, those waters that do not contain much carbonate are reduced by acid rain in pH and acid neutralizing capacity (ANC). Burger et al. (1998) established that approximately 6 % of chronically acid trout streams in Virginia originate in watersheds with low solubility siliciclastic rock. Because the geology of the alluvial fan in which the sinkhole ponds are located provides little buffering capacity, biologists became concerned that similar water chemistry might be found here and that this could pose a risk to the state endangered tiger salamander (*Ambystoma tigrinum*) and other pond inhabitants.

This two-year study was initiated in 1995 to develop a database of chemical solutes and concentrations for many of the ponds and to provide information on both seasonal and episodic variations in chemical composition. These data would then be available for use in the habitat assessment for the unique flora and fauna that are dependent on the sinkhole ponds system.

MATERIALS AND METHODS

The Shenandoah Valley Sinkhole Ponds (SVSP) system is located south of Stuart's Draft and Sherando, Virginia, in the Pedlar Ranger District of the George Washington National Forest. There are three complexes of ponds. The one most extensively studied is within an area known as Maple Flats in the vicinity of Canada Run (78°59' 00" W; 37° 58' 25" N). There are also ponds to the east near Orebank Run (Sherando Complex) and to the west near Love's Run (Love's Run Complex). To date, 36 ponds have been surveyed and these are numbered for this report by the name/number system of Buhlmann at al. (1999). A detailed map of the study locations may be found in their paper.

We collected water samples from the ponds in acid-washed HDPE bottles, which were stored at 4° C, and returned to the laboratory for analysis. We collected samples at least one m from the shoreline and 0.3 m below

Table 1. Summary of laboratory analysis methodology, methods and equipment used for the various chemical analyses.

	Instrumentation	Technique summary
pH	Orion 811 M with Orion glass combination electrode (Ross) MDL No 8102	pH recorded for samples in open beakers ≤ 0.01 units/min., electrodes calibrated twice daily with pH 4.01 and 7.00 buffer.
ANC	Orion 811 M with Orion glass combination electrode (Ross) MDL No 8102 and 10 mL glass microburet	Two end point (pH 4.50 and 4.20) titration with standardized 0.005 M HCl. Analysis run in duplicate. (APHA, 1995, method 2320)
chloride, sulfate, nitrate	Dionex 4500I ion chromatograph with AS4A column and AS4G column, AMMS suppressor	Injector volume: 50mL eluant: 1.8 mM Na_2HCO_3, 2mL min^{-1} analysis time = 10 min per sample. Run in triplicate. (± 2% RSD) (APHA, 1995, method 4110)
calcium magnesium	Varian spectr AA-30 atomic absorption spectrophotometer with Ca/Mg lamp	Atomic absorption analysis at 422.7 nm (Ca) and 285.2 nm (Mg) (APHA, 1995, method 3111D).
potassium, sodium	Varian spectr AA-30 atomic absorption spectrophotometer	Flame emission analysis at 766.5 nm (K) and 589 nm (Na) (APHA, 1995, method 3500-K and 3500-Na D).
aluminum	Varian spectr AA-30 with GTA-96 graphite tube analyzer	Graphite furnace analysis of total Al (APHA, 1995, method 3113)

the surface. Leaves, twigs, and other large foreign objects were excluded from collection bottles at the collection site. In the laboratory, water samples were filtered with 0.45 Fm polycarbonate filters prior to analysis. Fractions of the samples were made as 5% high purity nitric acid for metal analysis without delay after collection. We obtained samples from sinkhole ponds 2, 4, 11, 12, 13, 16, 17, 18, 21, Spring Pond, and the two manmade ponds known as Maple Flats South and Maple Flats North monthly for two years beginning in September, 1995. Each sample was collected near each mid-month at least two days following episodic precipitation events. Some ponds could not be sampled due to absence of water in dry periods or the inability to gain access due to storm events. We placed ISCO automatic water sample collectors for short periods at ponds 2, 13, 17, and 21 during spring 1997 to monitor episodic events. In addition to the twelve ponds monitored regularly, fourteen other ponds were sampled at least once. Ponds that were not sampled were either dry during the project period, were on private property, or were otherwise inaccessible.

The parameters monitored including pH (laboratory, 25°C), acid neutralizing capacity (ANC), total aluminum (Al_T), calcium (Ca_T), magnesium (Mg_T), sodium (Na_T), potassium (K_T), chloride (Cl^-), nitrate (NO_3^-) and sulfate (SO_4^{2-}) with samples filtered through a 0.45 Fm polycarbonate membrane. Analytical protocols and methods used for this work are described in Table 1. In addition to the above parameters, the Ca/H ratio was calculated by dividing the concentration of calcium by the concentration of hydronium with both ions expressed in units of acid-base microequivalents per liter (μeq/L).

Table 2. Water quality parameters for two-year average values. Results are reported as mean ± one standard deviation (number of samples). Standard deviations are not reported for ponds sampled fewer than four times.

Pond No.	pH (s.u.)	ANC (μeq/L)	Al_T (ppb)	Ca/H
2	5.43 ± 0.23 (21)	13.4 ±10.26 (20)	62 ± 51 (19)	5.66 ± 4.65 (22)
3	5.08	2.7	209	2.93
4	4.67 ± 0.23 (19)	-26.4 ± 16.0 (19)	95 ± 60 (18)	1.10 ±0.77 (20)
5	4.98	10.0	73	1.16
6	4.58	-30.4	90	0.52
7	4.86	-14.3	88	1.34
8	4.76 ± 0.33 (4)	-28.0 ± 37.0 (4)	129 ± 50 (4)	1.68 ± 1.80 (4)
9	4.74	-28.0	122	1.29
10	5.20 ± 0.18 (4)	-6.1 ± 11.8 (4)	115 ± 83 (4)	6.12 ± 4.40 (4)
11	5.43 ± 0.25 (28)	14.9 ± 20.8 (28)	40 ± 34 (27)	3.91 ± 2.42 (28)
12	5.38 ± 0.39 (23)	9.4 ± 9.4 (23)	36 ± 45 (22)	3.74 ± 3.67 (23)
13	5.39 ± 0.25 (31)	8.9 ± 10.8 (28)	59 ± 67 (27)	4.85 ± 3.50 (28)
14	5.00	-18.3	97	1.19
15	5.28	-9.6	135	2.27
16	5.26 ± 0.22 (25)	17.5 ± 6.5 (28)	77 ± 77 (23)	3.63 ± 3.11 (25)
17	5.29 ± 0.29 (25)	1.8 ± 8.5 (23)	53 ± 43 (22)	3.31 ± 2.70 (23)
18	4.89 ± 0.30 (22)	-9.7 ± 22.9 (22)	146 ± 135 (21)	1.70 ± 0.82 (22)
21	5.18 ± 0.33 (24)	2.0 ± 16.9 (24)	50 ± 40 (23)	1.96 ± 2.10 (24)
23	4.94	8.7	63	1.21
24	4.78	-26.0	90	1.58
25	4.85	-24.2	52	1.38
26	4.98	-1.1	135	2.36
27	5.19	-8.1	36	1.83
28	4.93	-13.7	99	1.57
Spring	5.17 ± 0.31 (25)	6.7 ± 11.2 (24)	36 ± 24 (23)	3.22 ± 3.38 (25)
MFS	6.00 ± 0.33 (25)	22.2 ± 12.0 25)	38 ± 46 (24)	35.35 ± 31.30 (25)
MFN	5.94 ± 0.27 (25)	18.7 ± 10.0 (25)	23 ± 18 (24)	25.35 ± 19.33 (25)
Mills	5.68	67.1	39	33.98

Table 3. Base cations two-year average values. Numbers as in Table 2. Standard deviations are not reported for ponds sampled fewer than four times.

Pond No.	Na (μeq/L)	K (μeq/L)	Mg (μeq/L)	Ca (μeq/L)
2	19.3 ± 4.8 (20)	17.4 ± 5.7 (20)	24.9 ± 6.1 (20)	21.1 ±6.3 (20)
3	21.0 (1)	15.3 (1)	28.8 (1)	24.4 (1)
4	19.3 (2)	16.4 (2)	20.5 (2)	17.4 (2)
5	21.0 ± 8.2 (19)	18.7 ± 9.8 (19)	19.2 ± 6.4 (19)	21.4 ± 5.6 (19)
6	14.8 (1)	8.1 (1)	15.7 (1)	13.7 (1)
7	16.7 (1)	12.9 (1)	14.3 (1)	18.5 (1)
8	20.9 ± 1.8 (4)	21.8 ± 13.8 (4)	16.9 ± 4.7 (4)	19.4 ± 7.5 (4)
9	23.7 (2)	21.6 (2)	27.9 (2)	23.0 (2)
10	22.2 ± 5.6 (4)	15.2 ±17.3 (4)	27.5 ±12.4 (4)	34.7 ± 22.0 (4)
11	19.4 ± 5.0 (29)	13.8 ± 4.5 (28)	15.8 ± 3.0 (28)	12.8 ± 4.5 (28)
12	20.4 ± 7.4 (23)	12.2 ± 4.3 (23)	15.0 ± 2.4 (23)	10.8 ± 4.0 (23)
13	20.4 ± 6.4 (28)	19.7 ± 9.1 (28)	22.9 ± 4.6 (28)	17.8 ± 5.0 (28)
14	24.3 (1)	22.8 (1)	11.9 (1)	11.9 (1)
15	20.1 (2)	9.8 (2)	33.5 (2)	40.7 (2)
16	22.4 ± 6.0 (24)	16.2 ± 6.0 (24)	24.8 ± 4.8 (24)	18.1 ± 7.9 (24)
17	21.6 ± 4.2 (23)	19.2 ± 7.3 (23)	22.4 ± 4.0 (23)	16.7 ± 5.7 (23)
18	25.9 ± 8.6 (22)	15.4 ± 10.3(21)	31.1 ± 19.7(22)	23.9 ± 18.1 (22)
21	23.5 ± 6.1 (24)	17.7 ± 8.0 (24)	14.1 ± 3.4 (24)	9.2 ± 4.0 (24)
23	21.4 (2)	16.2 (2)	25.7 (2)	13.6 (2)
24	22.1 (1)	16.8 (1)	21.7 (1)	9.6 (1)
25	20.0 (2)	25.6 (2)	22.2 (2)	19.8 (2)
26	26.8 (1)	34.9 (1)	48.2 (1)	24.7 (1)
27	10.0 (2)	11.5 (2)	16.7 (2)	12.0 (2)
28	14.6 (1)	22.9 (1)	22.2 (1)	18.5 (1)
Spring	20.2 ± 6.1 (24)	18.2 ± 7.2 (24)	16.6 ± 6.9 (24)	17.3 ± 10.3 (24)
MFS	18.6 ± 3.3 (25)	16.0 ± 4.3 (25)	19.9 ± 3.5 (25)	26.0 ± 6.3 (25)
MFN	18.8 ± 3.1 (25)	15.7 ± 3.7 (25)	20.5 ± 4.0 (25)	23.7 ± 5.1 (25)
Mills	19.3 (1)	9.6 (1)	27.9 (1)	71.0 (1)

Table 4. Acid anions two-year average values. Numbers as in Table 2. Standard deviations are not reported for ponds sampled fewer than four times. RCO_2H is calculated from the summation of ANC_{obs} and concentrations of base cations less the strong acid anions concentrations. It is a measure of dissolved organic acids. NC indicates "not calculated" due to excessive sulfate concentrations.

Pond No.	Cl^- (μeq/L)	NO_3^- (μeq/L)	SO_4^{2-} (μeq/L)	RCO_2H (μeq/L)
2	19.2 ± 2.7 (19)	1.8 ± 2.7 (19)	18.0 ± 5.0 (19)	30.3
3	22.8	4.7	22.2	37.1
4	18.3	0.0	102.5	NC
5	19.8 ± 5.6 (18)	1.0 ± 1.0 (18)	32.1 ± 16.7 (18)	17.4
6	17.8	0.2	31.3	33.4
7	15.4	0.0	15.3	46.0
8	21.1 ± 14.7 (4)	0.6 ± 1.5 (6)	47.1 ± 50.1 (4)	76.3
9	42.1	4.2	16.8	61.1
10	36.7 ± 17.2 (4)	1.9 ± 1.1 (4)	25.1 ± 21.9 (4)	42.1
11	19.2 ± 7.5 (27)	0.9 ± 1.1 (27)	12.5 ± 7.5 (27)	14.3
12	17.7 ± 5.3 (22)	1.1 ± .5 (22)	11.7 ± 6.6 (22)	18.5
13	21.9 ± 7.0 (27)	1.1 ± 1.3 (27)	19.5 ± 13.8	29.4
14	29.0	1.9	100.3	NC
15	30.3	0.8	67.3	15.3
16	23.4 ± 3.8 (23)	1.2 ± 1.3 (23)	18.2 ± 11.0 (23)	21.2
17	20.9 ± 5.1 (22)	1.7 ± 2.3 (22)	34.1 ± 6.8 (22)	21.4
18	33.6 ± 28.0 (21)	0.5 ± 0.9 (21)	13.5 ± 10.3 (21)	58.4
21	19.5 ± 3.8 (23)	0.6 ± 0.9 (23)	15.9 ± 14.2 (23)	26.5
23	15.5	0.9	36.5	15.3
24	9.6	0.8	90	NC
25	17.4	1.0	54.2	39
26	26.4	0.8	45.4	63.1
27	15.3	0.4	73.4	NC
28	15.8	0.0	37.8	38.3
Spring	20.6 ± 7.0 (23)	0.7 ± 1.0 (23)	18.2 ± 13.3 (23)	26.1
MFS	17.7 ± 3.3 (24)	0.7 ± 0.9 (24)	31.2 ± 11.4 (24)	8.7
MFN	19.1 ± 3.8 (24)	0.4 ± 0.7 (24)	30.9 ± 9.5 (24)	9.6
Mills	25.3	2.9	14.3	18.2

RESULTS AND DISCUSSION

Tables 2, 3, and 4 show two year average values for the water quality parameters (WQPs) collected during this study. Standard deviation values were calculated for WQP's that were measured four or more times during the study period and are included to show the scatter in the data. Table 2 includes pH values. The sinkhole ponds are all acidic with pH < 6; many of the ponds (48%) were below pH 5.0. About 20% of the ponds did not exceed this value during the two year period of sampling. Several factors contribute to the acidity of these ponds. Rainfall in Virginia is monitored at Charlottesville and the Shenandoah National Park within 100 km of the Big Levels area as part of the network of monitoring stations for the National Acid Deposition Program (NADP web site: http://nadp.sws.uiuc.edu/nadpdata/). We averaged the values for pH and other WQPs from these two stations for the two year period of this study and provided these values in Table 5. The low pH 4.5 average indicates high acid loading from precipitation in the watershed of the sinkhole ponds system. As the atmospherically-derived water moves down through the acid soils and low solubility bedrock, it encounters little natural carbonate or other buffers available to neutralize the acidity before it enters the ponds. It is important also to note most of the ponds have collected a considerable load of organic matter. This decomposing material also provides some acidity from humic, fulvic acids, and other organic acids.

Acid neutralizing capacity (ANC) is an operationally defined parameter. It is the sum of titratable bases in a natural water sample (French & Downey, 1993). In many systems natural buffer present in water originates from the

Table 5. Annual average rainfall values for common water chemistry parameters. Sources is NADP (NRSP-3) NTN database and is the average of 1995-97 at Shenandaoh National Park (SNP) and Charlottesville Stations. All solutes are expressed in micro-equivalent per liter concentration units (μeq/L).

Parameters	Average Values
pH	4.5
Ca_T	2.7
Mg_T	1.6
Na_T	6.3
K_T	0.4
Cl^-	6.8
NO_3^-	14.2
SO_4^{2-}	30.9

dissolution of carbonate bearing minerals such as calcite in the presence of CO_2 to form bicarbonate ion (HCO_3^-):

$$CaCO_3 + CO_2 + H_2O \rightleftharpoons Ca^{2+} + 2HCO_3^- \qquad (1)$$

Thus, the ANC titration gives results that may be interpreted as the bicarbonate acid-base equivalent. The charge balance expression for a natural water sample may be rearranged to give a useful mathematical expression to describe the relationship between major ionic solutes (Webb et al., 1989):

$$ANC\ (\mu eq/L) = \sum_{i}^{n} / Z_i / C_i - \sum_{j}^{m} / Z_i / A_i \qquad (2)$$

where: Z_i = charge of the ions, C_i = molar concentration of cations, and A_i = molar concentration of anions. The summation of cations and anions shows the contributions of individual solute ions:

$$\sum_{I}^{n} / Z_i / C_i = 2[Ca^{2+}] + 2[Mg^{2+}] = [Na^+] + [K^+] \qquad (3)$$

$$\sum_{j}^{m} / Z_i / A_i = [Cl^-] + [NO_3^-] + 2[SO_4^=] + [RCO_2H] \qquad (4)$$

Equations 3 and 4 show the summation of the concentrations of base cations and acid anions. ANC values for all the ponds are quite low as a result of a lack of base cations (Equation 3) and elevated levels of acid anions (Equation 4), with most being near zero or negative. The low values for base cations indicate a lack of mineral contribution to the pond water, which is an artifact of the insoluble bedrock geology. The high levels of sulfate are being deposited in the watershed by rainfall (Table 5) and this matches the elevated sulfate concentrations found in the ponds. Because sulfate concentration contributes in the negative direction to ANC (Equation 2), the importance of acid deposition on pond water quality is demonstrated. Finally, Table 4 shows high levels of organic acids which contribute to the low ANC; and a lack of nitrate contribution, even though it is a major component of rainfall. Nitrate is a nutrient and is consumed by growing plants (US EPA, 1994); thus concentrations are expected to be low (Galloway et al., 1984).

The relationship between pH and ANC is depicted in Figure 1. As ANC decreases, pH also decreases. About 50% of the ponds have pH and ANC values below levels acceptable for aquatic biota for most surface waters (Baker & Christensen, 1991). The remainder of the ponds have ANC values that could be reduced further by continued acid deposition. As sulfate ion increases, ANC decreases (Equation 2). Sulfate retention catchment basins

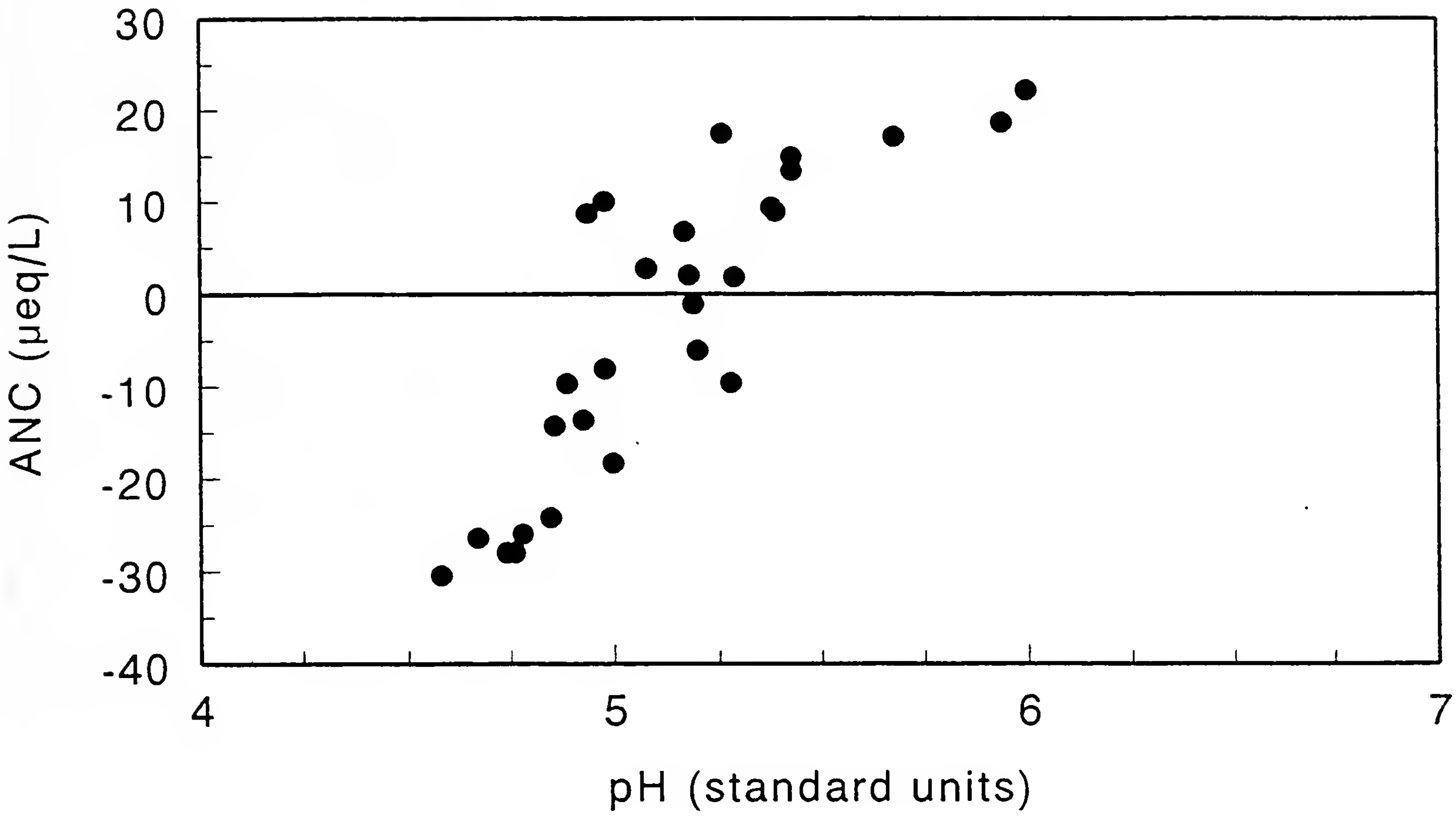

Fig. 1. Acid Neutralizing Capacity (ANC) observed for the ponds versus observed pH. Each data point represents the two-year average values for a single pond. The two points near pH 6 are for the manmade ponds: Maple Flats North and South, respectively, on Canada Run.

are probably not in equilibrium with atmospheric sulfate and continued deposition will ultimately exhaust the retention capacity (Bulger, 1998). Thus, even the ponds which have average pH > 5 will likely become more acidic.

Seasonal variation in pond water levels, the presence or absence of growing vegetation, and other factors are known to influence water chemistry in natural systems. *Ambystoma tigrinum* enters ponds from terrestrial burrows in winter to lay eggs, which hatch about a month later depending on temperature (Pague & Buhlmann, 1991). Larvae remain in the ponds several months, metamorphosing to sub-adults when the ephemeral ponds begin to dry. This period coincides with the lowest pH and ANC values for surface waters in Virginia. Figures 2, 3, and 4 shows the monthly pH, ANC and sulfate values found for three representative ponds. These three ponds were chosen for illustration for the following reasons: Pond 2 averages as one of the higher pH ponds and experiences dramatic fluctuations in pool level, Pond 18 is high in organic content, averages low in pH, and has less fluctuation in pool level, and Pond 21 is intermediate in pH with a relatively constant pool level. As pH and ANC values are generally low for the sinkhole ponds, little variation was observed due to seasonal cycling. Pond 2 increased slightly in pH and ANC values as it dried up in the summers of 1996 and 1997. High values were followed by lower values when the drying pool temporarily refilled due to summer storm events. In January 1996, a major snowstorm deposited up to two feet of snow in the Big Levels area. This snow was quite acidic (Downey, 1996, unpublished data) and when a warm front moved through in mid-January, a significant meltdown resulted. This caused a depression in pH and ANC, coupled with elevation of sulfate ion concentration. By the following month, values had returned to the pre-storm levels. This event suggested that episodic short term changes in water chemistry could be occurring that would not be observed by our monthly sampling protocols and that could adversely affect *A. tigrinum* and other aquatic biota. For this reason, several ponds were monitored with ISCO automatic sample collectors in the spring of 1997.

Figure 5 shows an episodic event recorded for Pond 2 that occurred in late February 1997. The pH was severely depressed from an acidic winter storm, yet the pond returned to pre-storm pH values within days. Additional events recorded for Ponds 13 and 21 (Figure 6) and Ponds 17 and 21 (Figure 7) demonstrated that when rainfall was of low pH and significant volume, pH depression followed by relatively rapid recovery. Figure 8 coincides with the data presented in Figure 7 and shows the sulfate increase that accompanies an acidic storm. It is not known whether the short term episodic events are detrimental to *A. tigrinum* or other aquatic life in the sinkhole

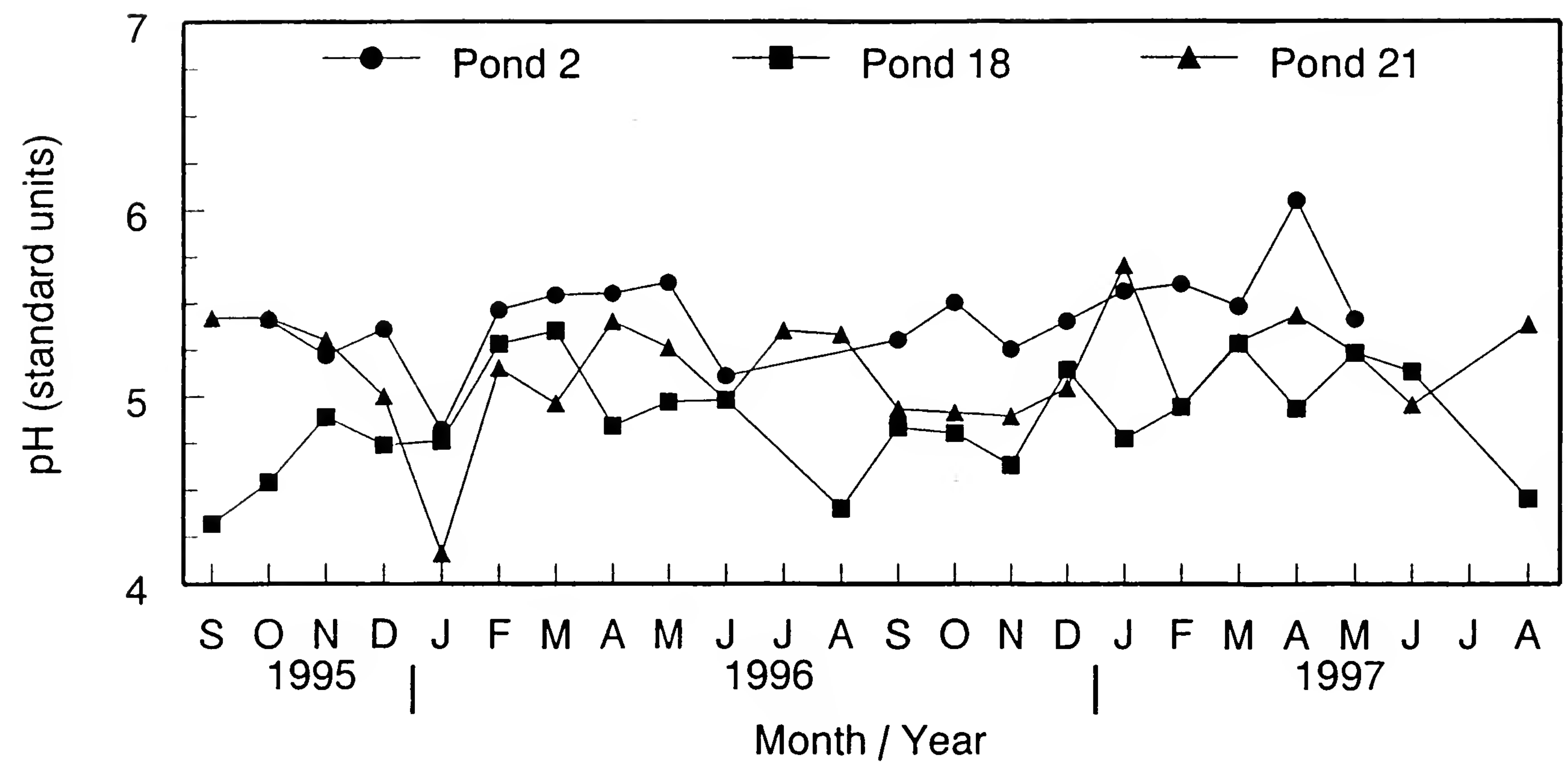

Fig. 2. Representative sinkhole ponds – pH versus month for a two-year period from September 1995 to August 1997. Data points are connected for clarity. Pond 2 was dry in July, August 1996, and June, July, August 1997.

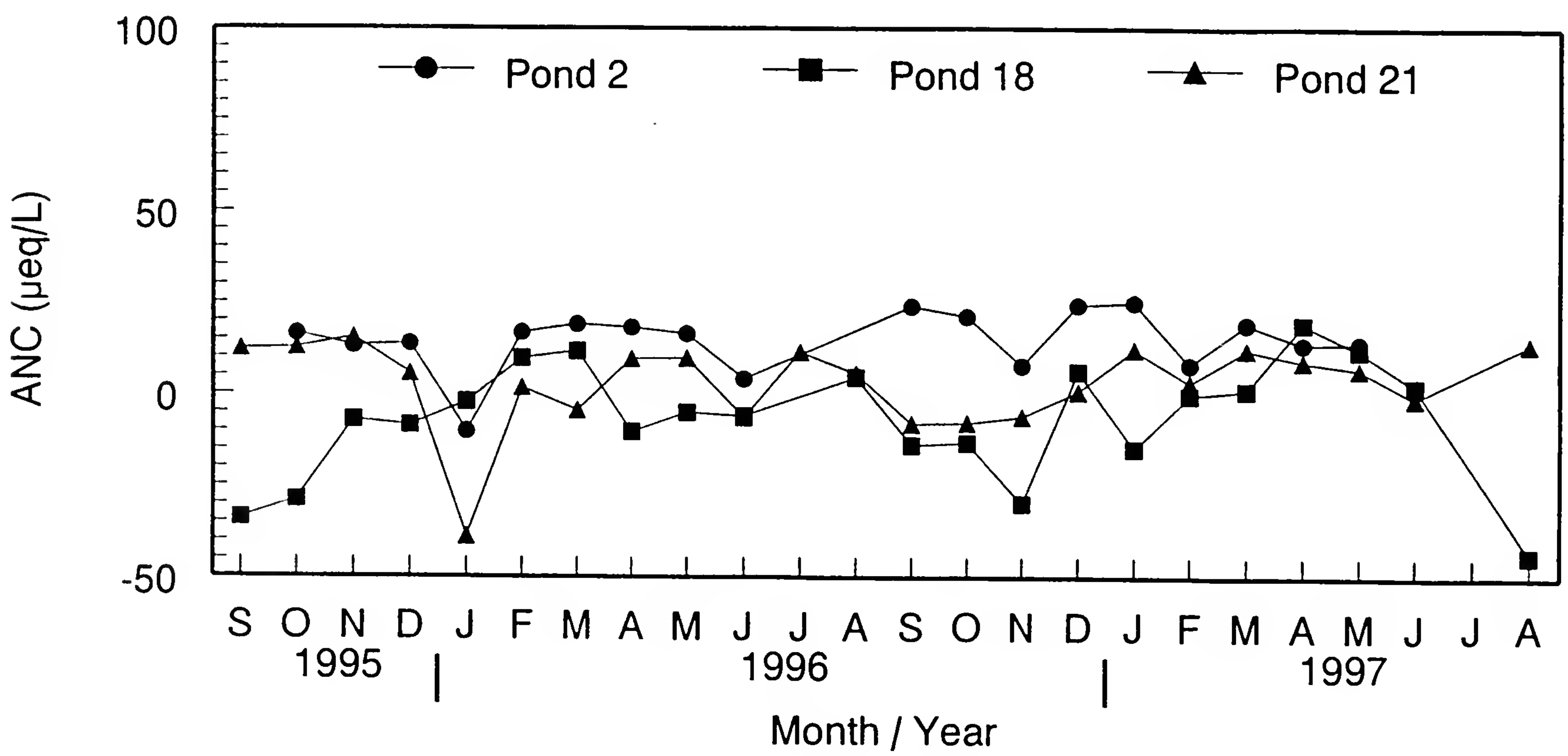

Fig. 3. Representative sinkhole ponds – ANC versus month for a two-year period from September 1995 to August 1997. Data points are connected for clarity. Dry periods for Pond 2 as in Fig. 2.

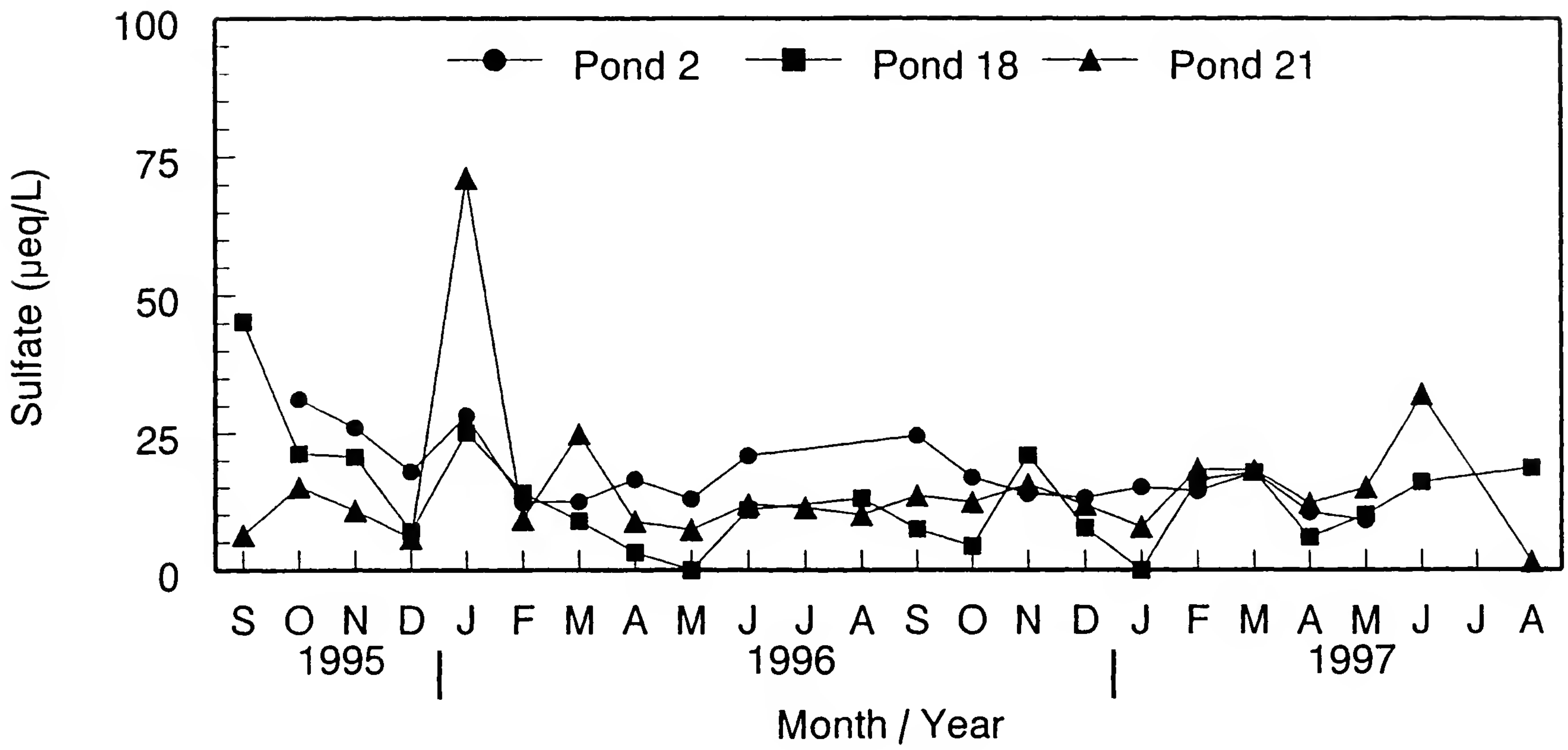

Fig. 4. Representative sinkhole ponds – Sulfate concentration versus month for a two-year period from September 1995 to August 1997. Data points are connected for clarity. Dry periods for Pond 2 as in Fig. 2.

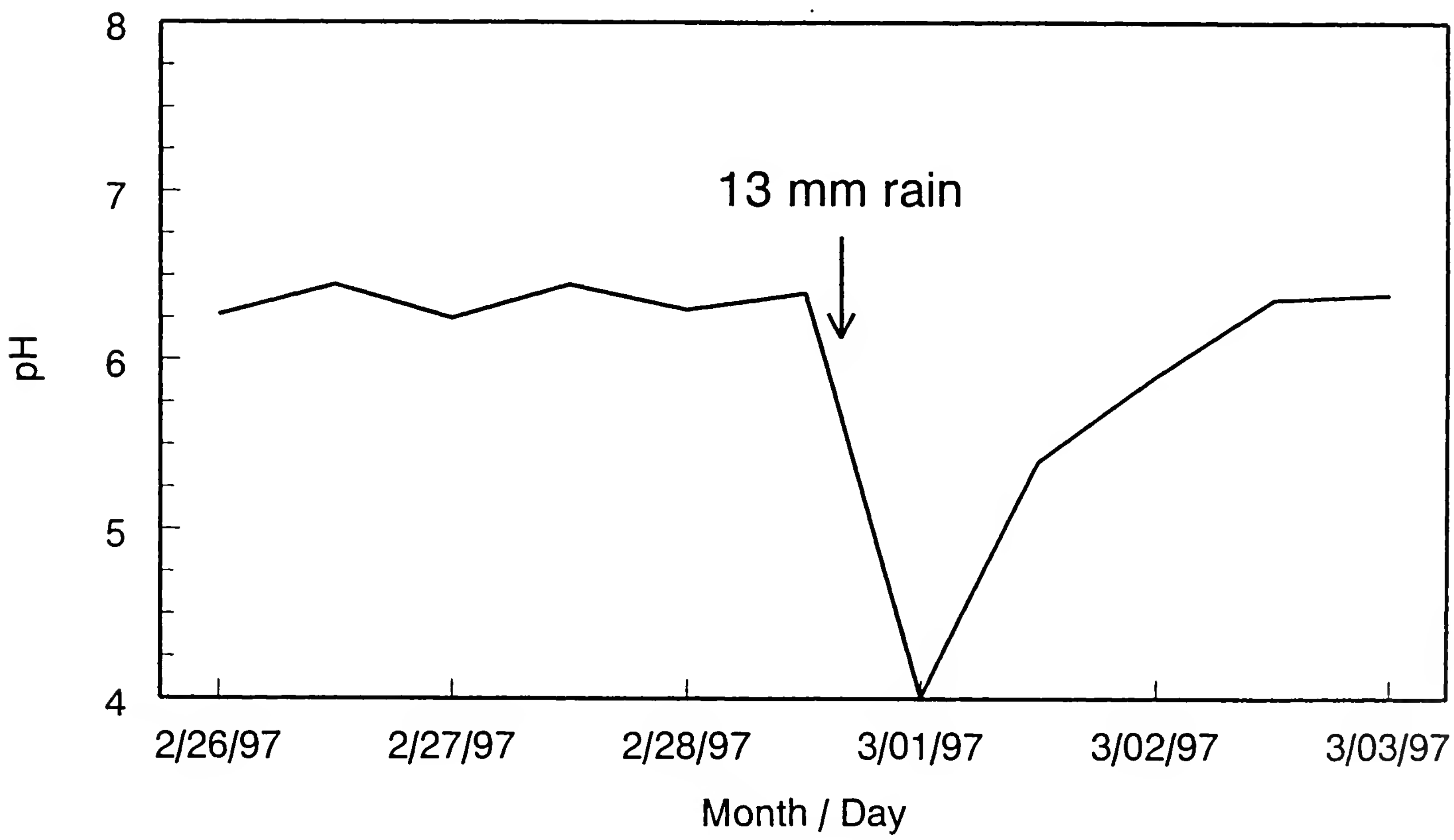

Fig. 5. Episodic event recorded for Pond 2. pH depression followed a 13 mm rain storm on February 28, 1997.

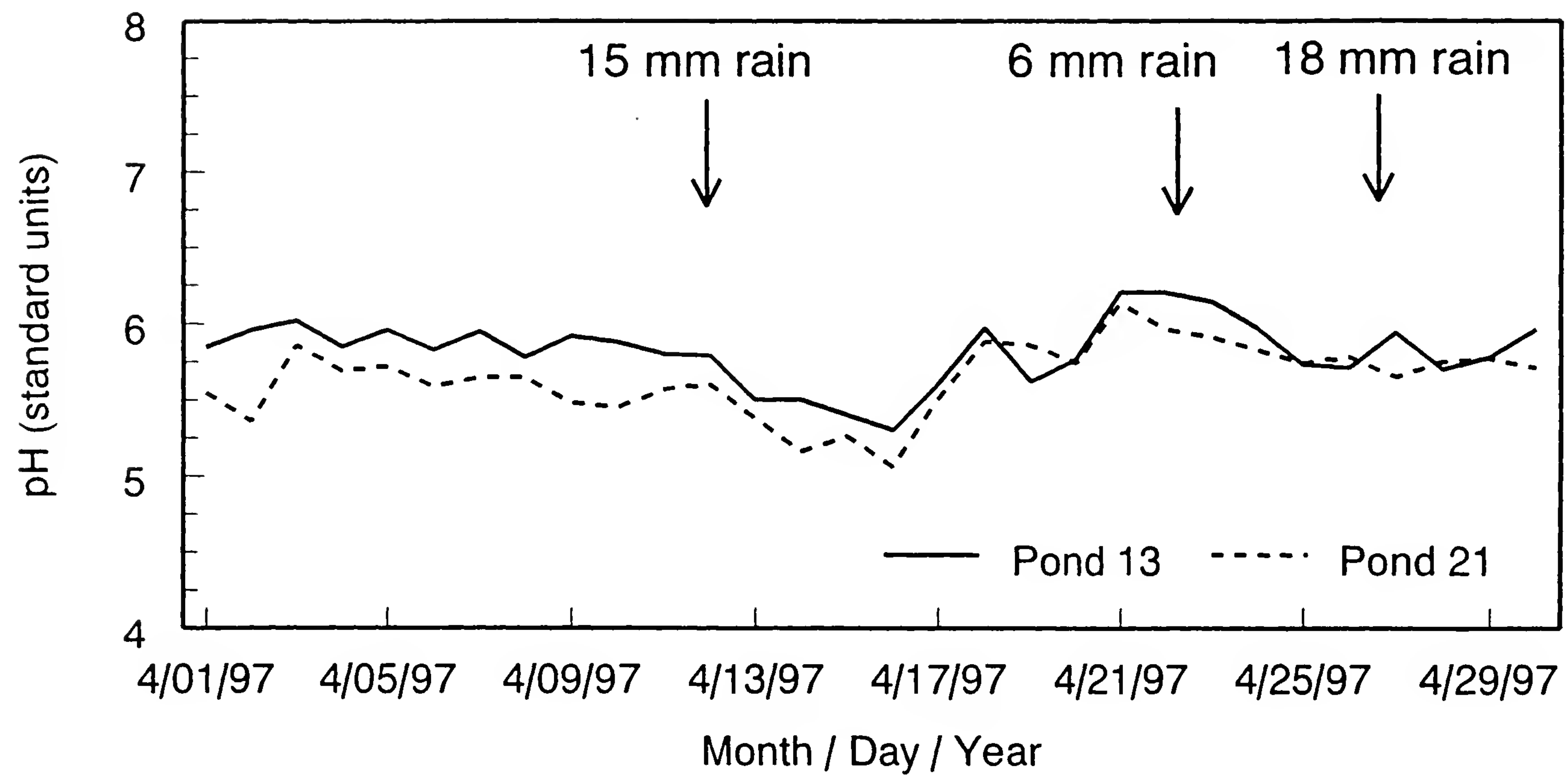

Fig. 6. Episodic events recorded for Ponds 13 (solid line) and Pond 21 (broken line) for three storms in April 1997 showing pH depression.

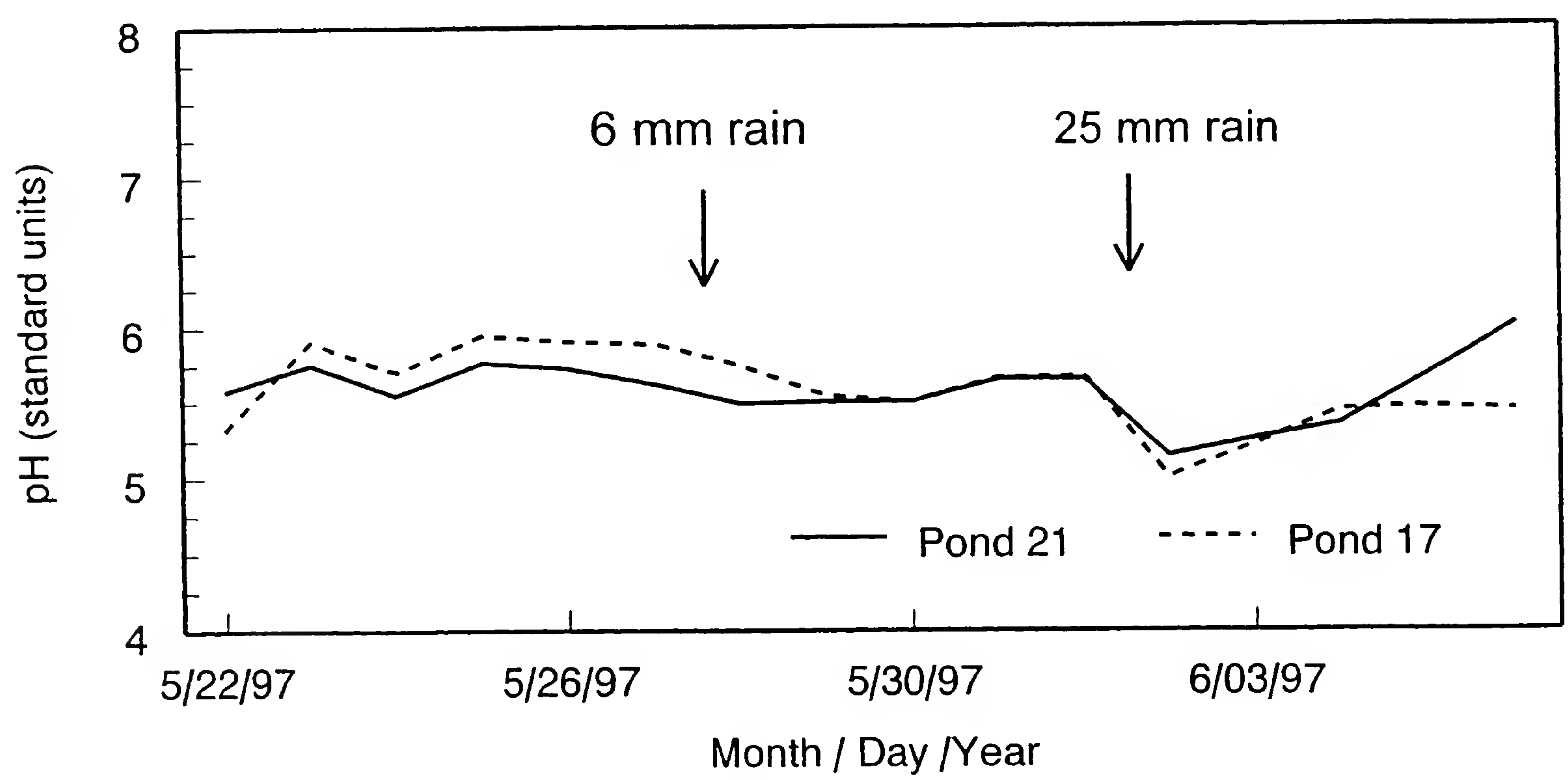

Fig. 7. pH values recorded for Pond 17 (broken line) and Pond 21 (solid line) for the period May 27 through June 6, 1997. The pH was depressed in both ponds after an acidic (< pH 5) storm event on June 1.

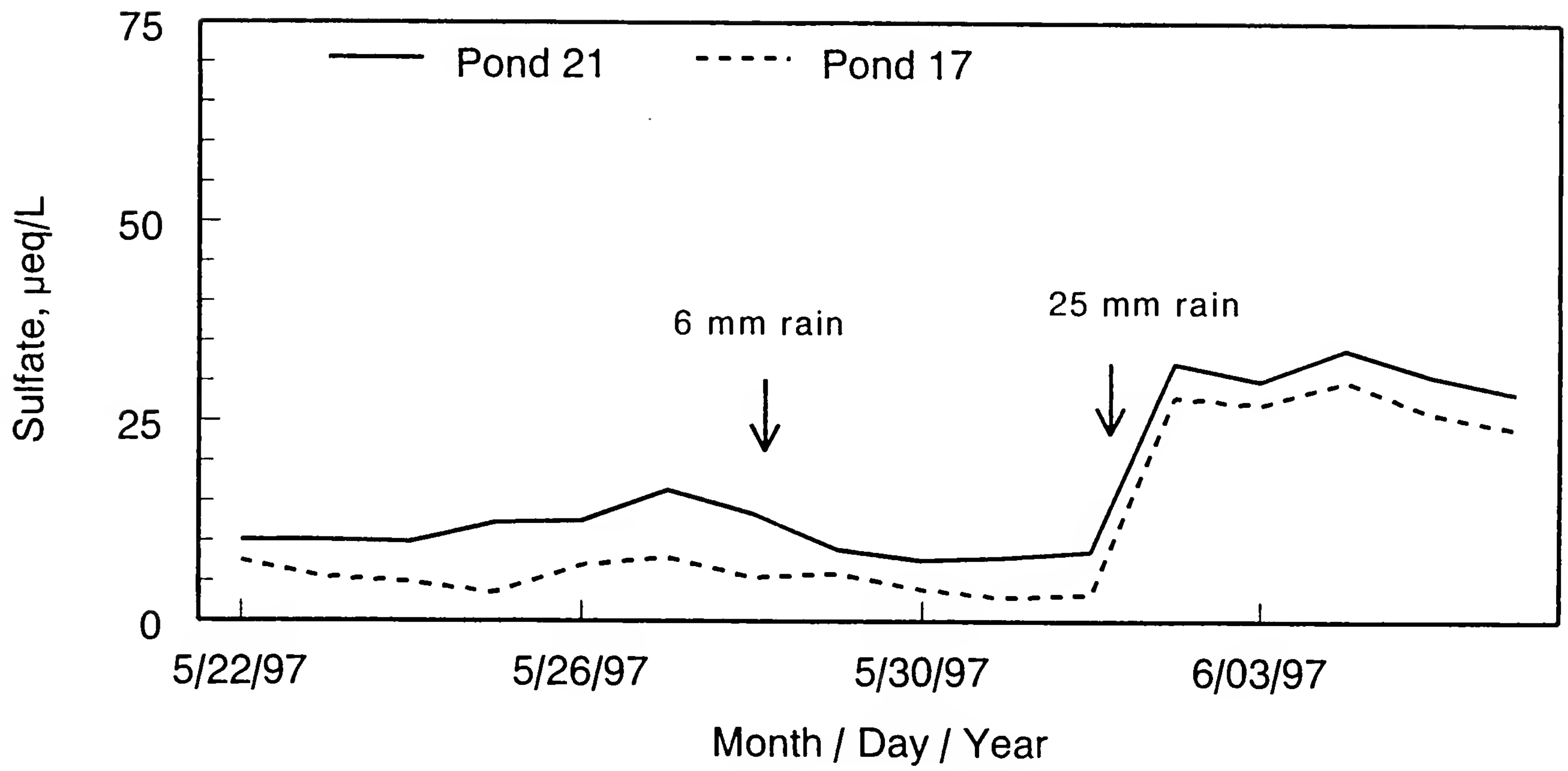

Fig. 8. Sulfate values recorded for Pond 17 (broken line) and Pond 21 (solid line) for the period May 27 through June 6, 1997. Sulfate ion concentration increased in both ponds after an acidic storm event on June 1.

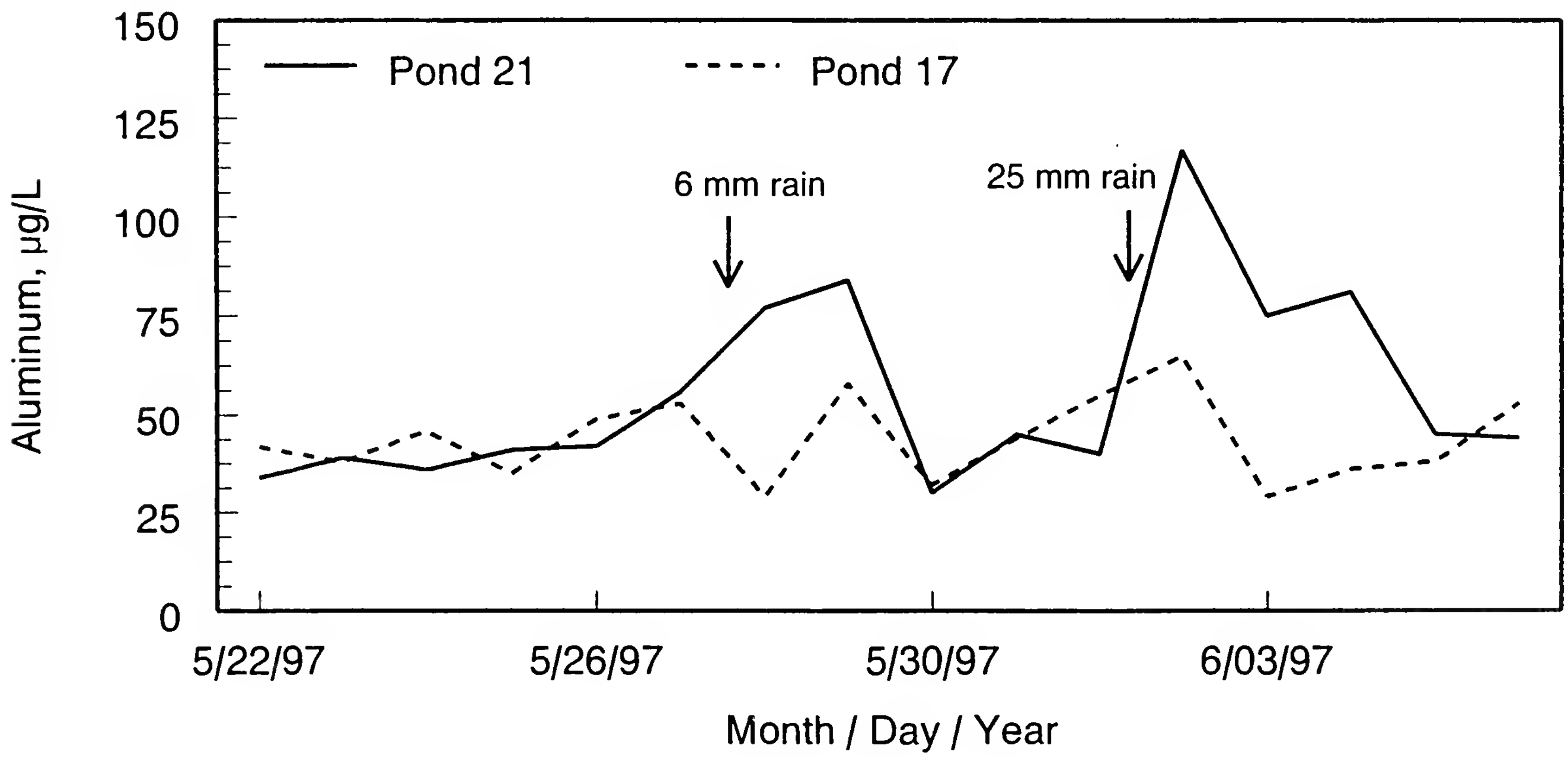

Fig. 9. Total aluminum values recorded for Pond 17 (broken line) and Pond 21 (solid line) for the period May 27 through June 6, 1997. Aluminum concentration increased in Pond 21, but did not signficantly change in Pond 17, after an acidic storm event on June 1.

ponds complex. Additional work is needed to integrate the knowledge of water chemistry to population density, individual behavior, reproductive success, and survivorship for *A. tigrinum*.

Table 2 includes the WQPs of aluminum and calculated calcium ion to hydronium ion ratio, Ca/H, which are important for the health of fisheries. Concentration of aluminum in natural water has been proven to be a major factor in the mortality of fish (Wood et al., 1988; McCahon et al., 1987). Aluminum dissolution from soils and minerals in a watershed increases as pH decreases (Cronan & Schofield, 1979). Calcium is beneficial as it inhibits aluminum binding by fish gills (Brown, 1982). The larger the Ca/H ratio, the better the survival rate even when toxic aluminum is elevated. Estimated values for no observed adverse effects on trout for these two WQPs are $Al_T < 100$ ppb and Ca/H > 6 (Menendez et al., 1996). It is not known if these values represent acceptable limits for *A. tigrinum*, but, if so, the two year average data in Table 2 suggest that Ca/H ratios in these ponds may be critically low. The low Ca/H ratio values confirm the lack of carbonate mineral dissolution (low calcium and high hydronium) contributing to water quality as described above. In most cases, the total aluminum is well below 150 ppb, although episodic events cause elevation in some ponds as shown in Fig. 9.

In the data sets of Tables 2, 3, and 4, the ponds MFS and MFN are the manmade wildlife ponds (South and North) on Canada Run which are situated in the middle of the Maple Flats sinkhole ponds complex. The pH and ANC values (Fig. 1) for these two ponds are significantly higher than for the sinkhole ponds. There is less organic acid, as Canada Run flows through these two ponds and flushes out organic matter. Other water quality parameters are also higher for these ponds than for the sinkhole ponds.

CONCLUSION

Water chemistry data collected for twenty-six natural sinkhole ponds and two man-made ponds for a two year period has revealed that all the natural ponds are chronically acidic with average values pH<6 and ANC< 20. About half the natural ponds were extremely acidic (pH<5, ANC< 0). Base cation and acid anion concentrations were also found to be low in all the ponds. Organic acids, atmospherically derived acid, and a lack of carbonate buffer from the acidic soils and bedrock geology of the system contribute to the poor water quality. Episodic precipitation events further decreased pH and other water quality parameters in these acidic ponds for short periods. The manmade ponds have slightly higher pH (pH 6) due to flushing from a tributary stream.

Although there are a number of species of plants and animals that are dependent on the ponds, this project was conducted primarily to provide data for assessing potential impacts from water chemistry on *A. tigrinum*. The low pH and poor water quality is a concern that could affect reproductive success and other aspects of the life cycle of the tiger salamander. Whiteman et al. (1995) indicated that *A. tigrinum* can tolerate relatively low pH values. They found embryo survival of > 70% at pH 4.5 and above, although they suggested sublethal effects could reduce hatchling survival. They also found an adult pH discrimination ability to ponds of higher pH. It is interesting to speculate that the higher pH of the two manmade ponds may be attractive to spawning adult salamanders from the nearby acidic sinkhole ponds. However, as these two ponds support predatory fish populations that could consume emigrating adult salamanders (Buhlmann et al., 1999), more study is needed to determine if they actually a pose a threat. It is not unreasonable to suggest their removal if such is the case.

ACKNOWLEDGEMENTS

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Plant Communities and Floristic Features of Sinkhole Ponds and Seepage Wetlands in Southeastern Augusta County, Virginia

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INTRODUCTION

Distinctive wetlands in the Big Levels - Maple Flats region of Augusta County, Virginia, have received considerable attention from botanists and ecologists during the past 60 years. Situated on deep, alluvial fan deposits overlying carbonate rocks along the western base of the Blue Ridge Mountains, these wetlands include natural depressions or sinkhole ponds formed through processes of karstic collapse and sedimentation, as well as seepage wetlands developed along streams draining the area. Freer (1933), Carr (1937, 1938, 1939, 1940a, 1940b), Rawlinson & Carr (1937), and Harvill (1972, 1973a, 1975) have noted the occurrence of Coastal Plain plants and disjunct northern plants in some of the ponds and seepages. Work in the Big Levels - Maple Flats region wetlands by the Virginia Department of Conservation and Recreation's Division of Natural Heritage (DCR-DNH) over the past decade has focused on inventory of rare taxa (Van Alstine & Ludwig, 1991; Van Alstine et al., 1992; Longbottom & Van Alstine, 1995; Van Alstine, 1996). In addition, a preliminary classification of plant communities in Shenandoah Valley sinkhole ponds, including some of those in the Big Levels - Maple Flats region, was prepared by Van Alstine & Rawinski (1992).

In this paper, we focus on two objectives to more fully characterize the vegetation of the Big Levels - Maple Flats region: 1) development of a provisional classification of the plant communities in undisturbed ponds and seepages; and 2) a phytogeographic analysis of all vascular plant taxa reported from these wetlands.

STUDY AREA

For the purposes of this study, the Big Levels - Maple Flats region is broadly defined to include the entire flank and toe of the Blue Ridge, from the Big Levels ridgeline on the south to the edge of alluvial fan deposits on the north (Fig. 1). This region is located in southeastern Augusta County, generally south of Stuarts Draft, east of Steeles Tavern, and west of Sherando. Topographically, it is characterized by broad, gentle mountain tops, steep rocky slopes and boulderfields, and gently sloping to nearly level terrain where the foot-slopes meet the Shenandoah Valley floor. Bedrock of the mountain slopes is mostly Cambrian-age quartzite of the Antietam Formation (Werner, 1966). Fan deposits of three different ages and consisting of cobble to boulder-sized gravels extend for approximately three miles from the lower mountain slopes to near the South River (Whittecar & Duffy, 1992). These alluvial deposits overlie dolomites and limestones of the Cambrian Shady and Elbrook formations. Both residual and alluvial soils of the area are strongly acidic and infertile. Subxeric to xeric conditions and oligotrophic oak-pine forest vegetation prevail over much of the landscape. However, more mesophytic forests and forested wetlands influenced by groundwater seepage occur along streams draining the Big Level flanks and mantle of foot-slope fans. One of the best known seepages, Magnolia Swamp (Carr, 1939), is situated near the outermost edge of fan deposits, approximately 8 km WSW of Stuarts Draft.

Local solution of underlying carbonate formations and reworking of surficial material by streams have resulted in the development of numerous natural ponds in the fan deposits around the foot of Big Levels (Rawinski et al., 1996). These ponds vary in size from less than 0.1 ha to over 1.0 ha. Pollen profiles from bottom sediments in two ponds demonstrate the continuous existence of pond habitats in this area over the past 15,000 years, as well as major shifts of local climate and vegetation during this period (Craig, 1969). Ponds that are particularly well

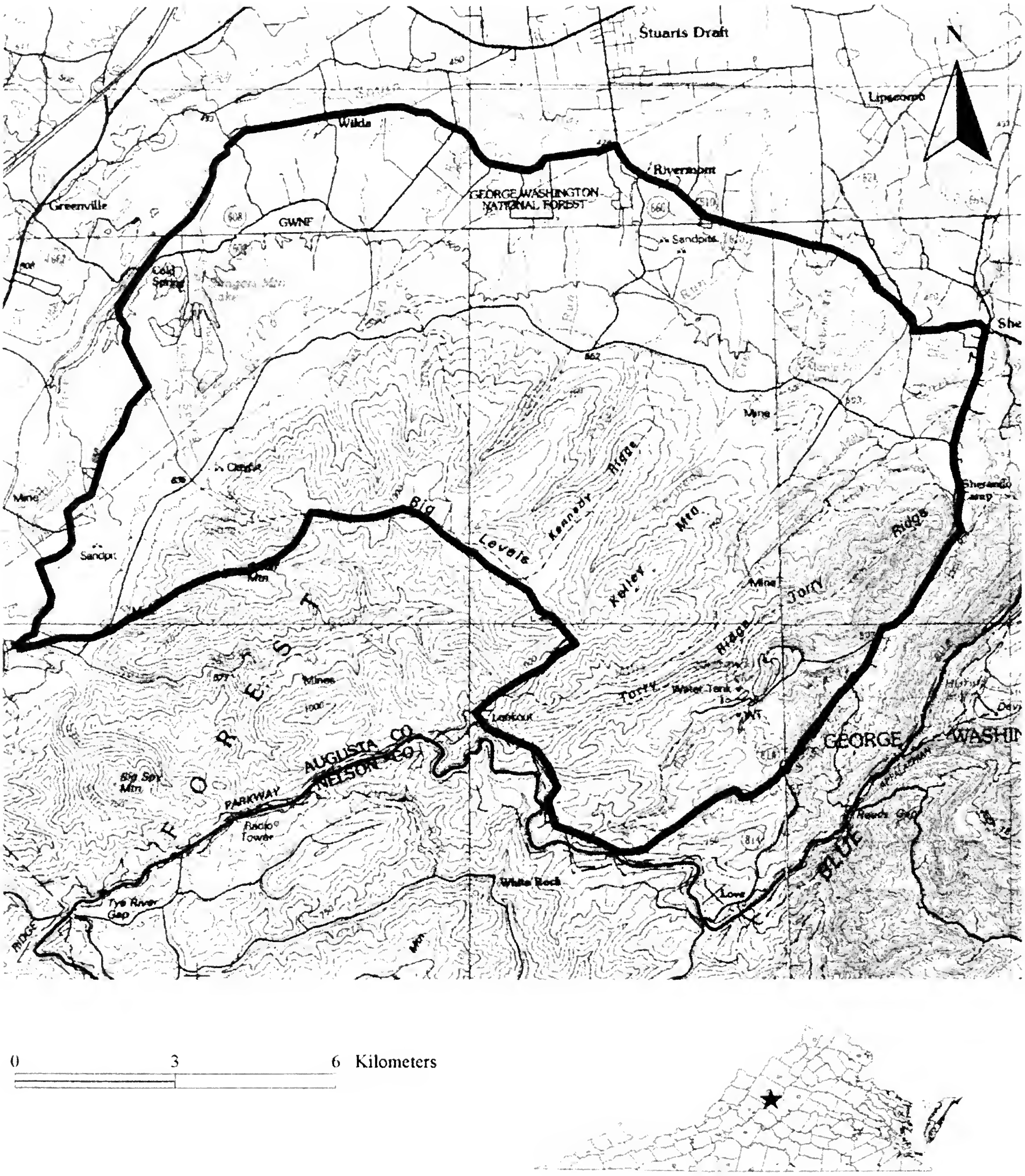

Fig. 1. Location of the Big Levels - Maple Flats region study area in Augusta County, Virginia.

known botanically include Deep Pond, Kennedy Mountain Meadow, Oak Pond, Quarles Pond, Spring Pond (Hack Pond), and the Twin Ponds (North and South) (Freer, 1933; Rawlinson & Carr, 1937; Craig, 1969; Harvill, 1973; Mohlenbrock, 1990; Knox, 1997).

The Big Levels - Maple Flats region study area is part of a larger depositional landscape that stretches along the western base of the Blue Ridge for approximately 90 km, from the Rockbridge/Augusta county line north to the southernmost part of Page County. Sinkhole ponds and seepage wetlands scattered throughout this larger area are refugia for many rare species and contribute significantly to the biological diversity of the region (Woodward & Hoffman, 1991).

MATERIALS AND METHODS

Floristic presence/absence data collected by DCR-DNH biologists and cooperators from 78 relatively undisturbed wetland vegetation stands provided the basis for a provisional classification of plant communities. These data represent 24 seepage wetland and 29 pond stands in the Big Levels - Maple Flats region, as well as 25 additional pond stands located elsewhere in Augusta and Rockingham Counties in ecologically similar landscapes. It was essential to include stands from outside the study area in order to make the pond classification as robust and regionally representative as possible.

Much of the available data consisted of species lists recorded from individual wetlands during the period 1990-1998. A few stands were quantitatively sampled using the releve method of plot sampling (sensu Peet et al., 1998) with 100 m^2 quadrats; these data were converted to presence/absence for consistency across the entire data set. Multiple visits were made to many of the ponds, and hydrologic conditions, soil composition, and other environmental factors were subjectively evaluated in the field during these visits. A-horizon soil samples were collected from 13 ponds, and the chemical analysis of these samples and six others collected by J.S. Knox was reported in Knox (1997). Hydrologic regime descriptors follow Cowardin et al. (1979). However, field observations indicate that the hydroperiods of many ponds are irregular and unpredictable, making definitive placement in Cowardin's hydrologic regimes difficult in some cases (Buhlmann et al., 1999) .

The limited scope of data made community analysis and interpretation somewhat problematic. Pond vegetation in the study area is complex and varies with distinct, often concentric hydrological zonation. Since species lists frequently reflect heterogeneous, within-pond composition and environments, a modified Braun-Blanquet tabular analysis (Westhoff & van der Maarel, 1973) was employed to identify groups of species that tend to co-occur under similar environmental conditions. Compositional relationships among these stands were further examined, and community type groupings validated, using Detrended Correspondence Analysis (DCA; Hill, 1979) implemented in the software program PC-ORD (version 3.18, McCune & Mefford, 1997). Traditional Braun-Blanquet tabular methods were used to define compositionally similar units in the seepage wetlands. The major units of the classification are treated simply as "community types," which are defined as units with similar floristic composition, physiognomy, and environmental relationships. In a few cases, community subtypes or variants are defined. Types and subtypes are named using up to five species with high constancy and diagnostic value. Community names reflect stand structure, with the taller species listed first. Nominal species in the same stratum are separated by a dash (-) while those in different strata are separated by a slash (/).

Because much of the supporting data was not collected from areas of standard size, was not quantitative, and did not include environmental measurements, compositional units defined in this study must be considered provisional. More intensive and rigorous sampling of these wetlands is needed to fully circumscribe these communities and their hierarchical relationships.

Phytogeographic analysis of the flora of the Big Levels - Maple Flats region is based on floristic data from 33 ponds and 24 seepage wetlands located within the study area. These data consist mostly of taxa collected or identified in the field by DCR-DNH biologists and cooperators. Data from older herbarium records and literature sources were also included for a few sites; therefore, not all of the listed taxa are currently known to be extant. Nomenclature follows Kartesz (1994). Species were sorted into geographic distribution groups using standard botanical manuals (Fernald, 1950; Radford et al., 1968; Gleason & Cronquist, 1991) and the Biota of North America Project species distribution maps available on the Internet (BONAP, 1998). Using these sources, along with atlases of the Virginia flora (Harvill et al., 1992) and West Virginia flora (West Virginia Nongame and Natural Heritage Program, 1997), we also evaluated whether each taxon's Augusta County occurrence represents an outlier from its continuous range. In addition to significantly disjunct taxa, outliers included some taxa which occur regularly east of the mountains in the Piedmont Plateau but are absent to rare on or west of the Blue Ridge. The percentage of the total Big Levels - Maple Flats region wetland flora attributable to each of nine geographic distributional groups, as well as the total number of outliers in all groups, was calculated. The same calculations were performed using the area's pond flora (exclud

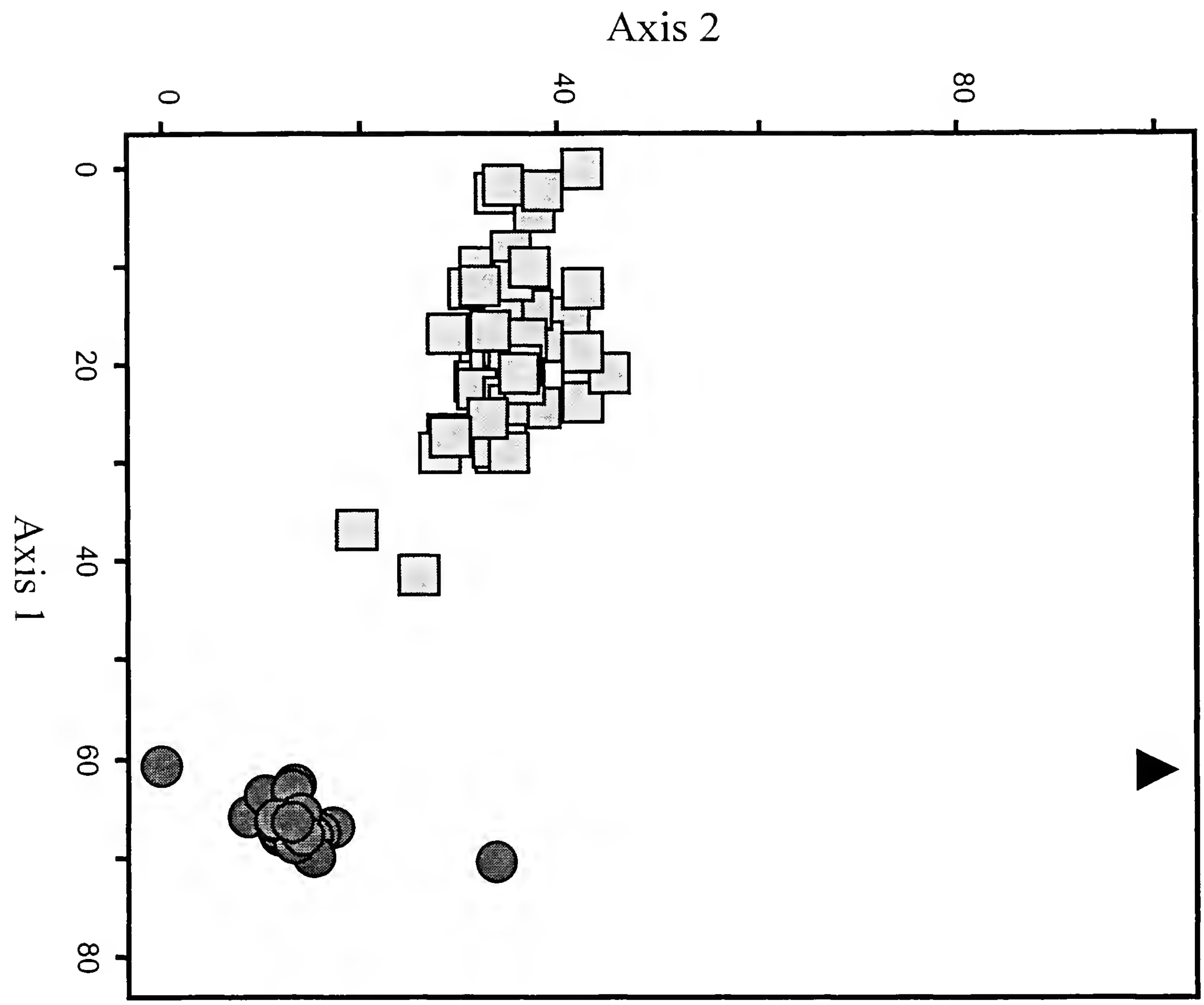

Fig. 2. Scatterplot diagram for DCA ordination showing the distribution of 78 relatively undisturbed wetlands on the first and second compositional axes. Wetland types: ▲ - calcareous fen; ● - forested swamp; ■ - sinkhole pond.

ing seepage wetlands) and using the group of taxa considered globally or state rare by DCR-DNH (Belden, 1998).

RESULTS AND DISCUSSION

Community Classification

Nine plant community types, one community subtype, and five variants were classified using tabular analysis and Detrended Correspondence Analysis of vegetation data. Distribution of all 78 stands on the first and second axes of a DCA ordination (Fig. 2) shows three compositional groupings: pond vegetation, indicated by squares; forested seepage wetlands, indicated by circles; and a single stand of fen-like shrub vegetation, indicated by a triangle.

Classification of pond vegetation is shown in Table 1, with the characteristic species of each community type enclosed by boxes. One subtype and two variants are nested within the community type boxes. Major boxes overlap where heterogeneous (e.g., zoned) vegetation and environments were recorded at sites; thus, some individual samples (ponds) contain more than one community type. A majority of ponds (indicated by the uppermost box) are wholly or partly occupied by a seasonally flooded zone with mineral soils that are exposed for a significant portion of the growing season. These environments support open woodland or herbaceous vegetation of the *Quercus palustris* / *Panicum rigidulum* var. *rigidulum* - *Panicum verrucosum* - *Eleocharis acicularis* community (type 1). Some ponds in this group also have a zone of deeper and more prolonged flooding supporting a *Cephalanthus occidentalis* / *Proserpinaca palustris* - *Polygonum hydropiperoides* community (type 2). The latter type also occupies marginal zones of five ponds characterized by a semipermanently flooded hydrologic regime, organic soils, and vegetation classified as a

Cephalanthus occidentalis / Dulichium arundinaceum community (type 3). Five ponds approach permanently flooded status and support a *Cephalanthus occidentalis / Torreyochloa pallida* community (type 4). Spring Pond, with a constant water level maintained by groundwater inputs, contained two unique compositional units (types 5 and 6). Another unique unit, characterized by nearly monospecific stands of *Carex barrattii* (type 7), was documented in an unusual seasonally flooded basin with organic soils.

When the compositional relationships of ponds were examined using DCA, comparable groupings are evident in an ordination diagram (Fig. 3). The two stands from Spring Pond performed as extreme outliers and distorted the initial scatterplot diagram. These were omitted from the final DCA analysis to better elucidate the relationships among the remaining stands. The group represented by triangles contains seasonally flooded ponds supporting community type 1 or both community types 1 and 2. The group represented by circles contains semipermanently flooded ponds supporting community type 3 or both community types 2 and 3. The group represented by squares are permanently flooded ponds supporting community type 4. The singular pond supporting community type 7 is represented by a diamond.

Classification of seepage wetlands is shown in Table 2. Vegetation and environments of the sample sites in this group are relatively homogeneous, and the units

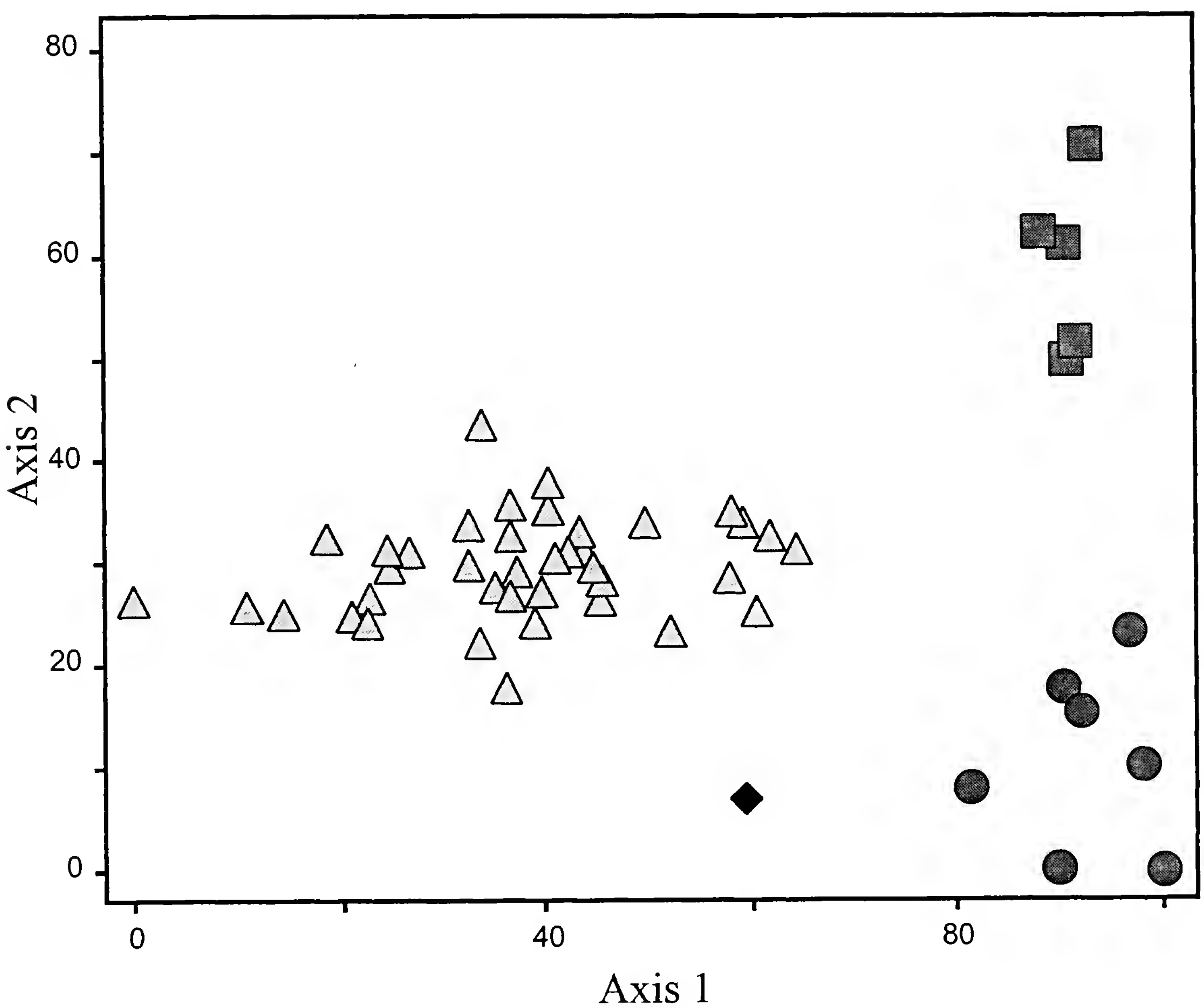

Fig. 3. Scatterplot diagram for DCA ordination showing the distribution of 52 relatively undisturbed ponds on the first and second compositional axes. Pond / community types: ▲ - wholly or partly seasonally flooded with mineral soil (ponds with community type 1 or both types 1 and 2); ● - semipermanently flooded with organic soil (ponds with community type 3 or both types 2 and 3); ■ - permanently flooded (community type 4); ◆ - seasonally flooded with organic soil (community type 7).

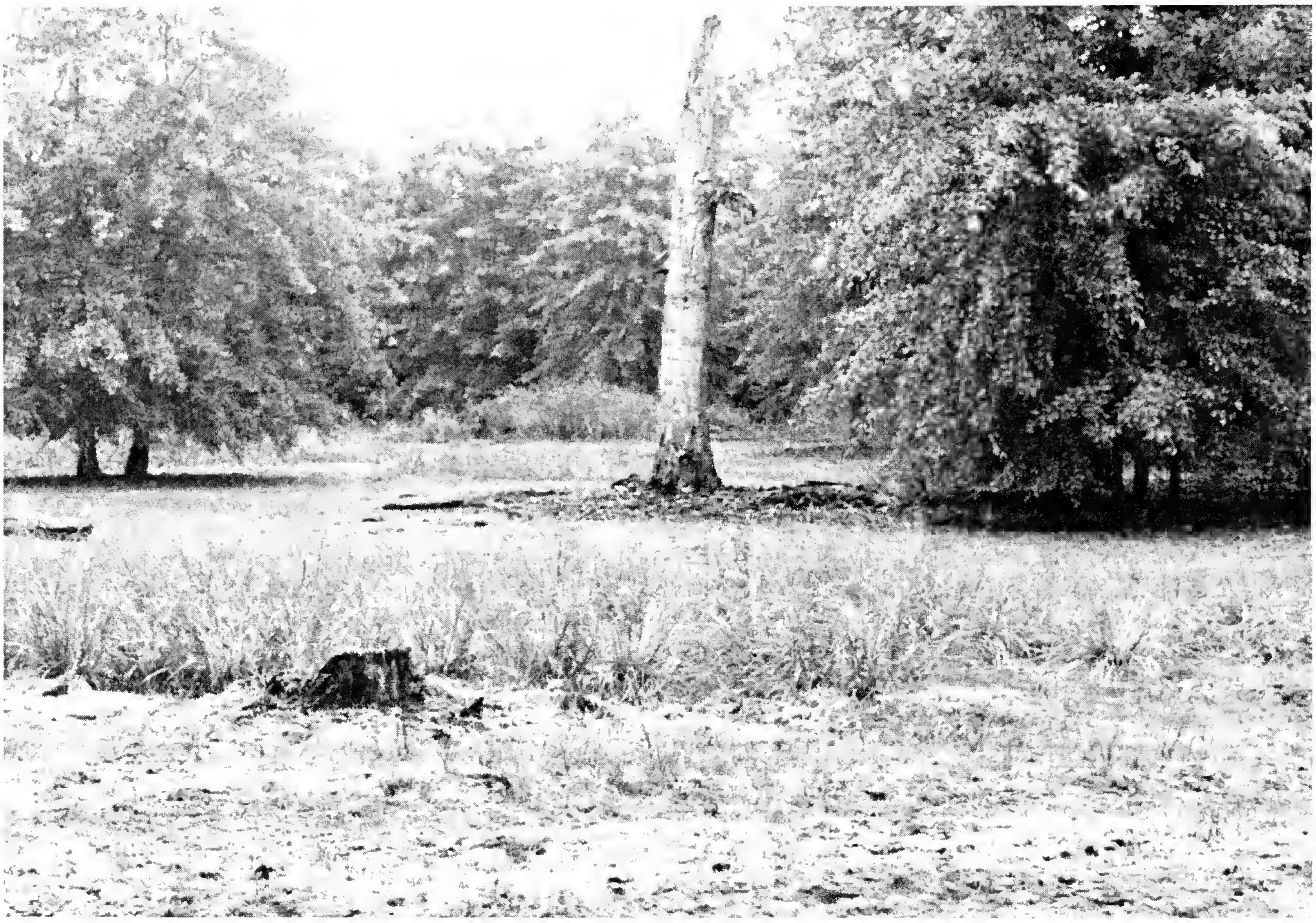

Fig. 4. Exsiccated, seasonally flooded pond supporting the *Quercus palustris* / *Panicum rigidulum* var. *rigidulum* - *Panicum verrucosum* - *Eleocharis acicularis* community (type 1; pin oak / tall flat panic grass - warty panic grass - least spikerush). Photo: Nancy E. Van Alstine.

represented by overlapping boxes have a hierarchical relationship. The single stand of calcareous shrub fen vegetation (type 9), represented by the box in the bottom right portion of the table, is floristically unique with the exception of one species. The remaining 23 stands, represented by the large box at the top of the table, contain forested seepage swamps classified as an *Acer rubrum* - *Nyssa sylvatica* - *Pinus rigida* / *Ilex verticillata* / *Osmunda cinnamomea* community (type 8). The three boxes in the middle of the table are overlapped by the large box above and show small groups of species largely confined to lower elevations (8a), middle elevations (8b), and the acidic portion of Magnolia Swamp (8c), respectively. These nested groups appear to represent relatively minor variants in a single, compositionally consistent unit with a large group of more or less constant, characteristic species.

Description of Community Types

All nine community types are found within the Big Levels - Maple Flats study area:

1. *Quercus palustris* / *Panicum rigidulum* var. *rigidulum* - *Panicum verrucosum* - *Eleocharis acicularis* community (pin oak / tall flat panic grass - warty panic grass - least spikerush)

Documented at 39 sites, this is the most prevalent plant community of the Shenandoah Valley sinkhole ponds in Augusta and Rockingham Counties. It is well represented in the study area at Kennedy Mountain Meadow, Twin Ponds (North and South), Oak Pond, and other sites. Physiognomy of these communities varies from open woodland with scattered individuals or groves

of *Quercus palustris*, to entirely herbaceous with trees confined to a marginal zone. The establishment and persistence of tree reproduction in these stands is episodic and probably associated with prolonged droughts. Shrubs are sparse or absent and the herbaceous flora is dominated by annual and perennial species adapted to seasonally flooded mineral soils. Soil chemistry at 19 sites is characterized by low pH (mean = 4.5), high levels of Al and As, and low levels of B, Ca, K, Mg, and P. Low pH in combination with high Al may impair the assimilation of macronutrients by plants (Knox, 1997). These data suggest that soil chemistry, in combination with hydrologic conditions, may produce unusual edaphic stresses that strongly influence community composition in these ponds. No comparable or similar vegetation is listed in The National Vegetation Classification (Anderson et al., 1998) or described for the southeastern United States by Weakley et al. (1998). Consequently, this community type is not only considered globally rare, but appears to be endemic to these Shenandoah Valley habitats. The distinctive *Salix humilis* var. *tristis* / *Schizachyrium scoparium* - *Sorghastrum nutans* community subtype (Dwarf Prairie Willow / Little Bluestem - Indian Grass) has affinities to prairie vegetation and is known from a single, intermittently flooded pond in the Maple Flats complex.

2. *Cephalanthus occidentalis* / *Proserpinaca palustris* - *Polygonum hydropiperoides* community (buttonbush / common mermaid-weed - mild water pepper)

Documented at 21 sites, this community occupies pond zones of relatively deep and/or long seasonal flooding and usually occurs in association with the

Fig. 5. Semipermanently flooded pond at Horseshoe Swamp, Maple Flats complex, supporting the *Cephalanthus occidentalis* / *Dulichium arundinaceum* community (type 3; buttonbush /three-way sedge). Photo: Gary P. Fleming.

previous type, or with the semipermanently flooded *Cephalanthus occidentalis / Dulichium arundinaceum* type below. Physiognomic expressions of this and other types with *Cephalanthus occidentalis* are quite variable, often comprising patch mosaics of shrubs and herbaceous openings. This community appears to be quite limited in the study area; small occurrences are located at several ponds, including Twin Pond North. It has some affinities to Coastal Plain vegetation types, but lacks many characteristic austral species.

3. *Cephalanthus occidentalis / Dulichium arundinaceum* community (buttonbush - three-way sedge)

This community type was documented at eight semipermanently flooded sites. Within the study area, excellent examples occur at Green Pond (Big Levels), Quarles Pond, Horseshoe Swamp (3 km W Sherando), and Hatton's Pond (4 km SW Stuarts Draft). Habitats are generally characterized by organic soils and retain surface water continuously in most years. The two nominal species occur in variable proportions, and at several sites *Cephalanthus occidentalis* is limited to marginal zones. Several other forbs and graminoids, including *Carex aquatilis* (water sedge), *Glyceria canadensis* (Canada mannagrass), *Glyceria obtusa* (coastal mannagrass), *Nuphar lutea* ssp. *advena* (spatterdock), *Scirpus ancistrochaetus* (northeastern bulrush; not documented within the study area), and *Scirpus torreyi* (Torrey's bulrush), are locally prominent. Stands dominated by *Carex aquatilis* and by *Scirpus torreyi* are classified as variants. The prevalence of *Carex aquatilis* at Green Pond on the Big Levels ridge crest may be related to a local weathering of Antietam quartzite that has exposed the less acidic Shady Formation (Werner, 1966; Wieboldt et al., 1998). Floristically and ecologically similar *Cephalanthus - Dulichium* ponds have been documented by DCR-DNH ecologists from several ridge crest depression ponds in the Virginia mountains. Coastal Plain ponds containing the two nominal species have also been documented, but their overall floristic composition is quite different from those of the mountain region (Rawinski, 1997).

4. *Cephalanthus occidentalis / Torreyochloa pallida* community (buttonbush - pale mannagrass)

This unit is a poorly known community type that occupies all or part of five ponds in the Big Levels - Maple Flats region. Stands are floristically depauperate and contain a high proportion of floating or submersed aquatic species. Dominants include the two nominal species, *Decodon verticillatus* (swamp loosestrife), *Eleocharis smallii* (creeping spikerush), *Glyceria acutiflora* (sharp-scaled mannagrass), *Potamogeton* spp. (pondweeds), *Proserpinaca palustris* (common mermaidweed), and *Utricularia* spp. (bladderworts). The habitats supporting this vegetation are permanently flooded, or nearly so. The relationships between this type and similar vegetation documented from the Virginia Coastal Plain (Rawinski, 1997) need further evaluation.

5. *Orontium aquaticum - Scirpus subterminalis* community (golden club - water bulrush)

This is an aquatic community dominated by *Orontium aquaticum* and also containing *Brasenia schreberi* (watershield), *Eleocharis robbinsii* (Robbins spikerush), *Eriocaulon aquaticum* (seven-angled pipewort), *Panicum hemitomon* (maidencane), *Scirpus subterminalis* (water bulrush), and *Woodwardia virginica* (Virginia chain fern). Hydrologic conditions supporting this type in the study area are unique to Spring Pond, a cold, permanently flooded pond with water levels constantly replenished by groundwater inputs. Very similar vegetation has been documented in oligotrophic, spring-fed, Coastal Plain millponds and beaver ponds in Delaware and eastern Virginia (Fleming & Van Alstine, 1994; J.C. Ludwig, pers. comm.). Consequently, the type's occurrence in the Big Levels - Maple Flats region perhaps could be considered a Coastal Plain "disjunct," reflecting the similar disjunct status of many of its component species and unusual edaphic conditions.

6. *Vaccinium macrocarpon - Pogonia ophioglossoides* community (large cranberry - rose pogonia)

This unit is a distinctive, ecotonal community occupying groundwater-saturated, locally floating peat and sphagnum mats along the south shoreline of Spring Pond. *Vaccinium macrocarpon* dominates in dense colonies. The bog-loving species *Calopogon tuberosus* (tuberous grass-pink), *Drosera rotundifolia* (round-leaved sundew), *Dulichium arundinaceum* (three-way sedge), *Eriophorum virginicum* (cotton-grass), *Juncus canadensis* (Canada rush), *Pogonia ophioglossoides*, *Triadenum virginicum* (marsh St. John's-wort), and *Xyris torta* (twisted yellow-eyed grass) occur as associates.

7. *Carex barrattii* community (Barratt's sedge)

This unit is confined to the drier, seasonally flooded portion of Horseshoe Swamp, which has an unusually deep, organic soil for this type of wetland. The community is dominated by nearly monospecific swards of the state-rare sedge *Carex barrattii*, with scattered associates

of *Bartonia paniculata* (twining bartonia), *Bartonia virginica* (yellow screwstem), *Spiraea tomentosa* (hardhack steeplebush), and *Triadenum virginicum*. One of the Shenandoah Valley's most pronounced Coastal Plain disjuncts, *Carex barrattii* is primarily found in the Coastal Plain from Connecticut to Virginia and formerly North Carolina, but has been documented at other disjunct inland sites with Coastal Plain affinities: Coffee County, Tennessee; Henderson County in the mountains of southwest North Carolina (where now extirpated); Pickens County in the mountains of South Carolina; and the mountains of Alabama and Georgia (Hill & Horn, 1997; Weakley, 1998).

8. *Acer rubrum - Nyssa sylvatica - Pinus rigida / Ilex verticillata / Osmunda cinnamomea* community (red maple - blackgum - pitch pine / winterberry / cinnamon fern)

This wetland forest occupies groundwater-saturated flats and low slopes along streams draining the study area. Outstanding examples occur along Canada Run, Kennedy Creek, Mills Creek, and Orebank Creek. These communities, commonly known as "seepage swamps," are most extensively developed in the area's gentler, lower elevation topography and have a variable canopy of *Acer rubrum*, *Nyssa sylvatica*, *Pinus rigida*, and *Liriodendron tulipifera* (tulip-poplar). A diversity of shade-tolerant shrubs, herbaceous acidiphiles, and mats of *Sphagnum* mosses are prevalent in the lower strata. Three variants with small groups of characteristic species are recognized (Table 2) and appear to be correlated with an elevational / topographic gradient. One of the most interesting variants occurs at Magnolia Swamp and features a notably disjunct population of the coastal plain tree *Magnolia virginiana* (sweetbay; Carr, 1939). This community type has many floristic affinities with saturated forests occurring in seepage- influenced wetlands of the inner Coastal Plain. The rare and beautiful plant *Helonias bullata* (swamp-pink) is locally abundant in seepage swamps of both geographic regions.

9. Calcareous Shrub Fen community (not formally named)

The unit is represented by a single stand of shrubby vegetation occupying a portion of Magnolia Swamp. This site is located at the extreme northern edge of alluvial fan deposits and is partly influenced by underlying carbonate rocks (Carr, 1939). This community, which intergrades with the adjacent, acidic seepage swamp, is dominated by the shrubs *Aronia arbutifolia* (red chokeberry) and *Rosa palustris* (swamp rose), with herbaceous openings containing the study area's only calcium-demanding plants. Among the pronounced calciphiles found here are *Carex conoidea* (field sedge), *Filipendula rubra* (queen-of-the-prairie), *Juncus brachycephalus* (small-headed rush), *Lysimachia quadriflora* (smooth loosestrife), *Parnassia grandifolia* (large-leaved grass-of-parnassus), *Pedicularis lanceolata* (swamp lousewort), and *Veronica scutellata* (marsh speedwell). This is a somewhat enigmatic community type, the interpretation of which is made difficult by co-occurring calciphiles and acidiphiles. More intensive study of within-site environmental dynamics and the floristic relationships of this stand to similar shrublands elsewhere will be required before the community can be formally classified.

Floristics and Phytogeography

A total of 274 vascular plant taxa, representing nine geographic distribution groups, was documented from wetlands of the Big Levels - Maple Flats study area (Table 3; Appendix A). The geographic groups are Widespread, Northern, Southeastern, Coastal Plain, Appalachian, Midwestern, Coastal Plain / Appalachian, Endemic, and Exotic. The distributional status of ten taxa is unknown due to uncertain taxonomic dispositions. It is important to note that phytogeographic assessments are based on distributions in eastern North America rather than rangewide or worldwide distributions.

Widespread taxa include those generally distributed in the eastern United States or eastern North America. The Northern group is comprised of taxa generally found in northeastern North America, northern North America, or circumboreally. These taxa typically extend south in the Appalachians or other highland regions, but do not reach the lower elevations of the southeastern United States. The Southeastern taxa occur commonly on the Atlantic and Gulf Coastal Plains but also extend more or less commonly into other provinces. They typically do not occur much farther north than Massachusetts, southern New York, Ohio, and Indiana, except sometimes along the Atlantic coast.

The more restricted taxa of the Coastal Plain group have distributions concentrated on the Atlantic and Gulf Coastal Plains, or just the Atlantic Coastal Plain. These plants are usually disjunct at scattered inland stations with Coastal Plain-like habitats and floristics, e.g., the Great Lakes region of northern Indiana and Michigan, and the Cumberland Plateau of central Tennessee (Peattie, 1922; Harvill, 1992). The Appalachian group consists of plants with distributions primarily in the Appalachian or southern Appalachian Mountains. Taxa of the Midwestern group have distributions centered west of the Appalachians in the northern part of the midwestern United States. With the exception of *Quercus palustris* (pin oak),

Fig. 6. Permanently flooded, spring-fed wetland at Spring Pond, Maple Flats complex, supporting the *Orontium aquaticum* - *Scirpus subterminalis* community (type 5; golden club - water bulrush). Photo: Gary P. Fleming.

a characteristic tree of glacially-leveled claypan wetlands in the midwest, plants of the Midwestern group reach their eastern range limits in the western or central Virginia uplands and are typically associated with prairies or prairie-like habitats in the main part of their range. The Coastal Plain / Appalachian category is represented by a single taxon, *Helonias bullata* (swamp-pink), whose range-wide distribution is fairly equally divided between the two geographic areas. Taxa restricted either to Virginia or to the Shenandoah Valley are included in the Endemic group.

Although Widespread taxa are most abundant in the overall wetland flora, significant numbers of Northern, Coastal Plain, and Southeastern taxa occur, along with a small number of interesting Midwestern plants and Virginia endemics (Table 3). Two long-range northern disjuncts, *Carex aquatilis* (water sedge) and *Cyperus dentatus* (toothed flatsedge), are documented in Virginia only from the Big Levels - Maple Flats study area. Several others, including *Arethusa bulbosa* (dragon's mouth), *Carex lasiocarpa* var. *americana* (slender sedge), and *Scirpus torreyi* (Torrey's bulrush), are known from only one or a few other sites in Virginia. The globally rare species *Echinodorus parvulus* (dwarf burhead) and the state rarities *Carex barrattii* (Barratt's sedge), *Eleocharis melanocarpa* (black-fruited spikerush), *Eleocharis robbinsii* (Robbins spikerush), *Lachnanthes caroliana* (redroot), *Panicum hemitomon* (maidencane), and *Utricularia fibrosa* (fibrous bladderwort) are particularly notable members of the Coastal Plain group. Only a small number of taxa have Midwestern affinities but two of these, *Filipendula rubra* (queen-of-the-prairie) and *Lysimachia quadriflora* (smooth loosestrife), are state rarities. *Helenium virginicum* (Virginia sneezeweed) and *Isoetes virginica* (Virginia quillwort) are endemic to Virginia. The former is endemic to seasonally flooded

sinkhole ponds in Augusta and Rockingham Counties, and is currently considered to be extant at 25 sites (Blake, 1936; Knox, 1995; Van Alstine, 1996; U.S. Fish and Wildlife Service, 1998). The type locality of *Isoetes virginica* is located within the Big Levels - Maple Flats study area, but the taxon is also documented from upland depression ponds of the southern Virginia Piedmont (Brunton et al., 1996; DCR-DNH, unpublished data).

The distributional status of the sinkhole pond flora alone was also analyzed (Table 3). The relative

Fig. 7. Forested seepage wetlands characterized by the *Acer rubrum - Nyssa sylvatica - Pinus rigida / Ilex verticillata / Osmunda cinnamomea* community (type 8; red maple - blackgum - pitch pine / winterberry / cinnamon fern) are common along streams draining the Big Levels - Maple Flats region. Photo: Gary P. Fleming.

importance of the four distributional groups containing the majority of the taxa found in the overall wetland flora remain the same for the pond flora. Slight shifts in group percentages result from an increase of Coastal Plain taxa, decreases of Northern and Midwestern taxa, and the loss of all taxa with a distinctly Appalachian distribution.

Taxa considered to be outliers from their continuous ranges constitute a significant percentage (20.4%) of the Big Levels - Maple Flats wetland flora (Appendix A). This percentage increased to 28.8% when the pond flora alone was evaluated. No one geographic distribution group predominated, and outliers were included in the Coastal Plain (18), Northern (15 taxa), Southeastern (13), Widespread (9), and Coastal Plain / Appalachian (1) groups.

Thirty-four taxa, or 12% of the wetland flora of the Big Levels - Maple Flats study area, are considered to be rare in Virginia by DCR-DNH (Table 3; Belden, 1998). Nearly half are of northern distribution, with Coastal Plain taxa comprising a smaller but significant percentage. Most (76%) of these rarities are associated with sinkhole ponds rather than seepage wetlands. Two species, *Lachnanthes caroliana* and *Lysimachia radicans*, are considered historical members of Virginia's flora due to long periods without documentation. Three species, *Helenium virginicum*, *Helonias bullata*, and *Echinodorus parvulus* are ranked as globally rare by The Nature Conservancy and network of Natural Heritage programs. Both *Helenium virginicum* and *Helonias bullata* are listed as threatened under the Federal Endangered Species Act and are state listed as endangered under the Virginia Endangered Plant and Insect Act.

Phytogeographic Discussion

The paleoecological work of Craig (1969) indicates that boreal-like forests and wetlands were prevalent in the early Holocene landscape of the study area. Pollen profiles show that *Picea*, *Pinus*, and *Abies* were abundant until approximately 9,500 years BP, when vegetation began to shift toward a *Quercus-Tsuga* assemblage perhaps resembling contemporary "northern hardwoods." A *Quercus-Pinus* assemblage, composed of the pollen of many species now occurring in the Big Levels - Maple Flats region, marks the upper parts of the profiles (Craig, 1969). The pollen record clearly suggests a warming post-glacial climate accompanied by major, if gradual, shifts in regional vegetation types. Although many genera present early in the record are no longer extant in the region, it seems reasonable to assume that at least some of the northern or boreal disjuncts presently occurring in the Big Levels - Maple Flats region are Pleistocene or early Holocene relicts that have persisted here in unusual wetland microhabitats.

The concentration of Coastal Plain disjuncts in the area is harder to explain. Harvill (1973b, 1992) has advanced the hypothesis that, in the mid-latitudes of the southeastern states, these taxa migrated inland when the boreal forest collapsed about 10,000 years BP but while the climate was still oceanic. When the climate turned continental about 8,000 to 9,000 years BP, or later during xerothermic intervals, most of the populations were extirpated from the interior, leaving relict colonies in localized, favorable habitats. These include certain wetland-laden areas of the Cumberland Plateau (particularly Coffee County, Tennessee), wetlands of the Blue Ridge escarpment of southwestern North Carolina (particularly Henderson County), and dunes and wetlands of the Great Lakes region in southwestern Michigan, northwestern Indiana, and northwestern Wisconsin -- all of which harbor notable occurrences of Coastal Plain species (Peattie, 1922; McLaughlin, 1932; Svenson, 1941; Kral, 1973; Harvill, 1984; Harvill, 1992; Weakley & Schafale, 1994).

The vegetational and phytogeographic history underlying contemporary distribution patterns is a fascinating subject that lies well beyond the scope of our objectives to more fully describe the present-day wetland vegetation and flora. Our analyses clearly demonstrate that the Big Levels - Maple Flats region supports a diversity of wetland habitats and community types, some of them globally rare or even endemic to this region. Botanical literature on the Big Levels - Maple Flats region has somewhat overemphasized the Coastal Plain element and underemphasized the northern element in relation to their actual numerical importance in this flora. More importantly, an objective enumeration of the flora reveals a remarkably high number of outlier taxa and rare species with several phytogeographic alliances. Although both Coastal Plain and northern elements are significant contributors to the region's biodiversity, it is the overall assemblage of geographically diverse outliers and unusual plant communities that makes these wetlands so biologically important and worthy of conservation.

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Table 1. Provisional classification of plant communities in 54 undisturbed sinkhole pond wetlands using floristic presence / absence data. Characteristic species of each community type are denoted by the boxes. Overlapping boxes indicate community and environmental zonation within ponds. An additional 80 inconstant and/or transgressive taxa were omitted from the table.

SITE:	P8	P17	P21	P24	P31	P36	P37	P44	P56	P61	P12	P13	P15	P28	P29	P1	P40	P41	P3	P5	P22	P23	P65	P66
1. QUERCUS PALUSTRIS / PANICUM RIGIDULUM VAR. RIGIDULUM - PANICUM VERRUCOSUM - ELEOCHARIS ACICULARIS Community - Open woodland/herbaceous vegetation																								
Quercus palustris	X	X					X			X	X	X	X			X	X						X	X
Panicum rigidulum var. rigidulum	X	X		X	X	X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Panicum verrucosum		X		X	X	X			X	X			X	X	X	X	X	X	X				X	X
Eleocharis acicularis		X	X	X	X	X	X		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X
Acer rubrum	X			X	X	X		X			X	X	X	X		X			X	X		X		
Nyssa sylvatica		X	X	X	X			X		X	X		X	X	X	X			X	X	X	X		X
Pinus rigida			X		X								X		X			X			X	X		
Agrostis perennans	X		X	X		X	X	X		X	X	X	X		X	X				X		X		X
Dichanthelium acuminatum	X		X			X	X	X			X	X	X	X	X	X				X	X	X		X
Diospyros virginiana	X	X						X	X			X			X	X			X	X	X	X		X
Hypericum boreale			X	X			X			X			X			X	X	X	X	X	X	X	X	
Helenium virginicum	X			X	X										X					X				
Panicum philadelphicum							X					X				X				X	X	X	X	
Bidens frondosa								X			X	X	X											
Smilax rotundifolia	X	X			X			X	X		X	X	X			X	X		X	X	X			X
Viola lanceolata	X	X	X	X	X			X		X	X	X	X		X	X	X	X	X	X	X	X		X
Erechtites hieraciifolia			X							X	X	X			X	X	X	X		X				
Aster dumosus	X		X				X	X		X	X				X						X	X		
Fimbristylis autumnalis						X			X	X						X	X		X			X		
Vaccinium corymbosum/fuscatum		X			X					X			X	X					X	X	X	X	X	X
Rhexia mariana / virginica						X		X		X					X						X	X		X
Community Subtype: *Salix humilis var. tristis / Schizachyrium scoparium - Sorghastrum nutans* - Intermittently flooded shrubland / herbaceous vegetation with prairie affinities.																								
Salix humilis var. tristis																								
Schizachyrium scoparium																								
Sorghastrum nutans																								
Baptisia tinctoria																								
Polygala nuttallii																								
Pteridium aquilinum v. lat.																								
2. CEPHALANTHUS OCCIDENTALIS / PROSERPINACA PALUSTRIS - POLYGONUM HYDROPIPEROIDES Community - Shrubland or herbaceous vegetation of seasonally flooded to																								
Cephalanthus occidentalis																			X	X	X	X		
Proserpinaca palustris														X		X		X						
Polygonum hydropiperoides											X	X				X	X							
Juncus canadensis																								
Eleocharis melanocarpa																								
Eleocharis smallii															X									
Glyceria acutiflora																								
Leersia oryzoides																								
Polygonum amphibium																								
Scirpus cyperinus													X											
Bidens discoidea																								
Woodwardia virginica																								
3. CEPHALANTHUS OCCIDENTALIS / DULICHIUM ARUNDINACEUM Community; Variants dominated by Carex aquatilis and Scirpus torreyi are indicated by the internal boxes -																								
Dulichium arundinaceum																								
Nuphar luteum																								
Scirpus ancistrochaetus																								
Triadenum virginicum																								
Utricularia sp.																								
Eleocharis robbinsii																								
Scirpus torreyi																								
Carex aquatilis																								
Glyceria canadensis																								
Potamogeton pulcher											X													
Utricularia gibba																								
Eleocharis quadrangulata																								
Glyceria obtusa																								
4. CEPHALANTHUS OCCIDENTALIS / TORREYOCHLOA PALLIDA Community - Semipermanently to permanently flooded shrubland and herbaceous vegetation with many floating/aquatic spp.																								
Torreyochloa pallida																								
Decodon verticillatus																								
Potamogeton sp.																								
Potamogeton oakesianus																								
Utricularia radiata																								
5. ORONTIUM AQUATICUM - SCIRPUS SUBTERMINALIS Community - Floating/aquatic herbaceous vegetation documented only from the permanently flooded portions of Spring Pond.																								
Orontium aquaticum																								
Scirpus subterminalis																								
Panicum hemitomon																								
Brasenia schreberi																								
Eriocaulon aquaticum							X																	
6. VACCINIUM MACROCARPON - POGONIA OPHIOGLOSSOIDES Community - Ecotonal shrubland and herbaceous vegetation of floating sphagnous peat mat along edge of Spring Pond																								
Vaccinium macrocarpon																								
Pogonia ophioglossoides																								
Calopogon tuberosus																								
Cuscuta compacta																								
Drosera rotundifolia																								
Eriophorum virginicum																								
Xyris torta																								
7. CAREX BARRATTII Community - Nearly monospecific, seasonally flooded herbaceous vegetation dominated by the nominal species; documented from Horseshoe Swamp																								
Carex barrattii																								
Bartonia paniculata																								
Bartonia virginica																								
Spiraea tomentosa																								

Table 1. Continued.

P64	P4	P6	P7	P14	P16	P18	P25	P30	P39	P42	P49	P26	P35	P2	P50	P58	P62	P47	P63	P60	P46	P27	P51	P52	P53	P54	P55	P57	P59

of shortly seasonally flooded ponds and pond zones

P64	P4	P6	P7	P14	P16	P18	P25	P30	P39	P42	P49	P26	P35	P2	P50	P58	P62	P47	P63	P60	P46	P27	P51	P52	P53	P54	P55	P57	P59
X	X			X	X	X				X	X		X					X			X								X
	X	X	X	X	X	X		X	X	X	X	X		X															
		X	X	X	X	X	X	X		X	X	X	X	X															
	X	X	X	X	X	X	X		X	X	X	X	X	X															
	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X			X				X	X			X
	X	X	X	X							X	X	X	X															
		X	X		X			X						X				X											X
X			X					X																					X
X		X	X					X			X	X																	
X	X		X		X	X			X		X	X		X															
	X	X	X	X	X	X		X	X	X	X		X	X										X					
			X	X		X		X	X	X	X		X																
	X		X	X																									
	X	X	X					X	X					X															
X	X		X	X		X	X	X	X	X				X				X											
X	X	X	X	X	X	X		X	X	X				X															
	X	X						X						X															
X			X						X																				
						X							X																
X	X			X	X	X		X		X				X				X											
			X					X			X		X																X
X																													
X																													
X																													
X																													
X																													
X																													

semipermanently flooded ponds and pond zones

P64	P4	P6	P7	P14	P16	P18	P25	P30	P39	P42	P49	P26	P35	P2	P50	P58	P62	P47	P63	P60	P46	P27	P51	P52	P53	P54	P55	P57	P59
	X	X			X	X	X		X	X	X	X	X	X	X	X	X	X		X	X	X		X	X	X			
	X	X		X	X		X	X	X	X		X	X	X	X	X	X		X			X	X						
	X	X	X				X	X	X			X	X	X	X	X	X	X	X										
		X						X		X		X		X	X	X	X	X		X								X	
			X						X	X	X					X			X										
			X						X	X	X			X	X	X	X	X			X	X	X		X				
					X		X			X		X		X		X	X					X		X					
	X	X							X	X	X	X		X	X						X								
	X			X	X				X					X															
	X		X	X	X	X		X			X				X														
										X		X		X	X														
										X		X		X							X				X	X	X	X	

Shrubland or herbaceous vegetation of semipermanently flooded ponds and pond zones

P64	P4	P6	P7	P14	P16	P18	P25	P30	P39	P42	P49	P26	P35	P2	P50	P58	P62	P47	P63	P60	P46	P27	P51	P52	P53	P54	P55	P57	P59
												X		X	X	X	X	X	X	X	X			X		X		X	
																	X	X	X		X								
															X			X	X		X								
														X	X	X		X		X	X					X		X	X
													X	X		X		X		X	X	X							
											X		X		X	X											X		
																		X	X										
																				X									
																X					X							X	
																	X		X										
																	X		X									X	
																		X											
															X														

P64	P4	P6	P7	P14	P16	P18	P25	P30	P39	P42	P49	P26	P35	P2	P50	P58	P62	P47	P63	P60	P46	P27	P51	P52	P53	P54	P55	P57	P59
																						X	X	X	X	X			
																									X	X		X	
																	X						X	X					
													X									X							
																								X					

P64	P4	P6	P7	P14	P16	P18	P25	P30	P39	P42	P49	P26	P35	P2	P50	P58	P62	P47	P63	P60	P46	P27	P51	P52	P53	P54	P55	P57	P59
																											X		
													X														X		
																											X		
															X												X		
													X														X		

P64	P4	P6	P7	P14	P16	P18	P25	P30	P39	P42	P49	P26	P35	P2	P50	P58	P62	P47	P63	P60	P46	P27	P51	P52	P53	P54	P55	P57	P59
															X					X								X	
																												X	
																												X	
																												X	
																												X	
																												X	
																												X	

P64	P4	P6	P7	P14	P16	P18	P25	P30	P39	P42	P49	P26	P35	P2	P50	P58	P62	P47	P63	P60	P46	P27	P51	P52	P53	P54	P55	P57	P59
																													X
																													X
																		X										X	X
																													X

Table 2. Provisional classification of plant communities in 24 seepage wetlands using floristic presence/absence data. Characteristic species of each community type and three hierarchically nested variants of one are denoted by the boxes. An additional 60 inconstant and/or transgressive taxa were omitted from the table.

SITE:	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S16	S14	S15	S17	S18	S19	S20	S21	S22	S23	S24	S2	S1
8. ACER RUBRUM - NYSSA SYLVATICA - PINUS RIGIDA / ILEX VERTICILLATA / OSMUNDA CINNAMOMEA Community																								
Forest vegetation of groundwater-saturated stream bottoms in acidic alluvial and colluvial soils; low to middle elevations																								
Acer rubrum	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Nyssa sylvatica	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X		X	
Pinus rigida	X	X	X		X	X		X	X	X	X	X		X	X	X	X	X					X	
Ilex verticillata		X	X		X	X	X		X	X	X	X	X	X	X			X	X	X	X	X	X	
Osmunda cinnamomea		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Liriodendron tulipifera	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	
Kalmia latifolia	X	X	X			X		X	X	X	X	X	X	X	X	X		X	X	X	X	X		
Alnus serrulata	X	X					X		X	X	X	X		X	X			X			X		X	X
Viburnum nudum var. cassinoides	X	X			X	X			X	X	X	X	X	X	X	X	X	X	X	X	X		X	
Viburnum dentatum	X	X	X	X	X	X	X		X	X	X		X						X	X	X		X	
Menziesia pilosa		X	X	X				X	X			X	X	X	X	X	X	X	X	X	X			
Chionanthus virginicus	X	X			X				X	X		X						X	X	X				
Smilax sp.	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X			X			
Rubus hispidus	X			X	X	X		X	X		X			X			X		X	X	X	X	X	
Carex gynandra		X	X	X				X	X			X		X			X				X	X	X	
Helonias bullata	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
Thelypteris noveboracensis	X	X	X	X		X			X			X	X	X	X			X	X	X	X	X		
Medeola virginiana	X	X	X	X	X	X	X	X	X		X	X	X			X	X				X	X	X	
Lycopodium obscurum	X		X				X	X	X	X	X				X		X	X	X	X				
Osmunda regalis var. spectabilis		X	X	X		X			X		X	X			X		X	X	X	X	X	X	X	
Parnassia asarifolia	X		X	X	X	X		X		X		X			X			X	X	X	X			
Viola cucullata		X		X	X	X	X					X					X				X	X	X	
Sphagnum spp.	X		X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	
8a. Characteristic species of low elevation variant:																								
Amianthium muscitoxicum	X		X		X					X														
Brachyelytrum erectum		X	X		X				X		X										X			
Carex debilis	X	X	X							X		X												
Carex folliculata			X	X																				
Carex intumescens		X	X				X				X											X		
Cypripedium acaule			X			X		X		X		X												
Gaylussacia frondosa	X			X																			X	
Lindera benzoin		X	X	X		X	X				X						X						X	
Platanthera ciliaris				X		X				X		X												
Platanthera clavellata	X	X	X	X	X	X		X			X		X					X					X	
Uvularia sessilifolia	X	X	X		X	X			X	X	X											X		
Viburnum nudum var. nudum					X		X																	
Viola primulifolia	X		X	X							X	X											X	
8b. Characteristic species of middle elevation variant:																								
Aster acuminatus												X	X	X	X			X	X	X				
Betula lenta						X						X	X	X				X			X	X		
Magnolia acuminata		X							X	X					X				X	X	X			
Pinus strobus														X				X	X	X				
Rhododendron catawbiense								X		X		X	X			X		X			X	X		
Rhododendron viscosum																	X	X	X	X		X	X	
8c. Characteristic species of "Magnolia Swamp" variant:																								
Magnolia virginiana																							X	
Arethusa bulbosa																							X	
Dulichium arundinaceum																							X	
Juncus effusus																							X	
Parthenocissus quinquefolia																							X	
Triadenum virginicum																							X	
Woodwardia areolata																							X	

Table 2. Continued. Provisional classification of plant communities in 24 seepage wetlands using floristic presence/absence data. Characteristic species of each community type and three hierarchially nested variants of one are denoted by the boxes. An additional 60 inconstant and/or transgressive taxa were omitted from the table.

SITE:	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S16	S14	S15	S17	S18	S19	S20	S21	S22	S23	S24	S2	S1
9. CALCAREOUS FEN Community (not formally named)																								
Saturated shrubland vegetation in stream bottom seepage zone; calcareous soil and/or groundwater ; known in this region only from Magnolia Swamp, in part																								
Alisma subcordatum																								X
Aronia arbutifolia																							X	X
Caltha palustris																								X
Campanula aparinoides																								X
Cardamine bulbosa																								X
Carex buxbaumii																								X
Carex conoidea																								X
Carex lurida																								X
Carex stricta		X																						X
Cornus amomum																								X
Eleocharis tenuis																								X
Filipendula rubra																								X
Hydrocotyle americana																								X
Iris versicolor																								X
Juncus brachycephalus																								X
Lysimachia quadriflora																								X
Lysimachia terrestris																								X
Parnassia grandifolia																								X
Pedicularis lanceolata																								X
Peltandra virginica																								X
Physocarpus opulifolius																								X
Ranunculus hispidus var. caricetorum																								X
Rosa palustris																								X
Sagittaria rigida																								X
Selaginella apoda																								X
Senecio aureus																								X
Veronica scutellata																								X

Table 3. Phytogeographical summary of the vascular plant taxa in wetlands of the Big Levels - Maple Flats region. Rare taxa are those designated as such by DCR-DNH (Belden, 1998).

DISTRIBU-TIONAL GROUP	NO. OF TAXA -ALL WETLANDS	% OF TOTAL FLORA	NO. OF POND TAXA	% OF TOTAL POND TAXA	NO. OF RARE TAXA	% OF TOTAL RARE TAXA
Widely Distributed	133	48.54	82	52.56	3	8.82
Northern	53	19.34	25	16.03	16	47.06
Southeastern	39	14.23	21	13.46	2	5.88
Coastal Plain	20	7.30	17	10.90	8	23.53
Appalachian	8	2.91	0	0	0	0
Midwestern	4	1.46	1	0.64	2	5.88
Exotic	4	1.46	1	0.64	-	-
Coastal Plain /Appalachian	1	0.36	0	0	1	2.94
Endemic	2	0.73	2	1.28	2	5.88
Unknown	10	3.65	7	4.49	-	-
Totals	274	100.00	156	100.00	34	100.00

Appendix A. Floristics of the wetlands of the Big Levels - Maple Flats region, Augusta County, Virginia. Distributional Status: W= Widespread; N= Northern; SE = Southeastern; CP = Coastal Plain; A= Appalachian; MW = Midwestern; CP/A = Coastal Plain /Appalachian; E = Endemic to Virginia; EX= Exotic; and U = Unknown. Note: Some pond taxa may also be in seepages. See text for explanation of Outlier category and Belden (1998) for explanation of Rarity Status codes.

Taxon	Distributional Status	Pond Taxa	Outlier	Rarity Status
PTERIDOPHYTA				
ASPLENIACEAE				
Asplenium platyneuron (L.) B.S.P.	W	X		
BLECHNACEAE				
Woodwardia areolata (L.) T. Moore	SE		X	
Woodwardia virginica (L.)Sm.	W	X	X	
DENNSTAEDTIACEAE				
Pteridium aquilinum (L.) Kuhn var. *latiusculum* (Desv.) Underwood *ex* Heller	W	X		
DRYOPTERIDACEAE				
Dryopteris cristata (L.) Gray	N			
ISOETACEAE				
Isoetes virginica N. E. Pfeiffer	E	X		G1Q / S1?
LYCOPODIACEAE				
Huperzia lucidula (Michx.) Trevisan	N			
Lycopodiella inundata (L.) Holub	N	X	X	G5 / S1
Lycopodium clavatum L.	N			
Lycopodium obscurum L.	W			
OSMUNDACEAE				
Osmunda cinnamomea L. var. *cinnamomea*	W	X		
Osmunda regalis L. var. *spectabilis* (Willd.) Gray	W			
SELAGINELLACEAE				
Selaginella apoda (L.) Spring	SE			
THELYPTERIDACEAE				
Thelypteris noveboracensis (L.) Nieuwl.	W			
Thelypteris palustris var. *pubescens* (Lawson) Fern.	W			
SPERMOPHYTA: GYMNOSPERMAE				
PINACEAE				
Pinus rigida P. Mill.	N	X		
Pinus strobus L.	N	X		
Tsuga canadensis (L.) Carr.	N			
SPERMOPHYTA: ANGIOSPERMAE				
Monocotyledoneae				
ALISMATACEAE				
Alisma subcordatum Raf.	W			
Echinodorus parvulus Engelm.	CP	X	X	G3 / S1
Sagittaria rigida Pursh	N			G5 / S1
ARACEAE				
Arisaema triphyllum (L.) Schott	W	X		
Orontium aquaticum L.	CP	X		
Peltandra virginica (L.) Schott	W			
Symplocarpus foetidus (L.) Salisb. *ex* Nutt.	N			

Taxon	Distributional Status	Pond Taxa	Outlier	Rarity Status
CYPERACEAE				
Carex aquatilis Wahlenb.	N	X	X	G5 / S1
Carex barrattii Schwein. & Torr.	CP	X	X	G4 / S2
Carex buxbaumii Wahlenb.	N	X		G5 / S2
Carex conoidea Schkuhr *ex* Willd.	N			G4 / S1S2
Carex debilis Michx.	SE			
Carex echinata Murr. ssp. *echinata*	N	X		
Carex folliculata L.	N	X		
Carex gynandra Schwein.	N			
Carex intumescens Rudge	W			
Carex lasiocarpa Ehrh. var. *americana* Fern.	N	X	X	G5 / S1
Carex leptalea Wahlenb.	W			
Carex longii Mackenzie	W		X	
Carex lupulina Muhl. *ex* Willd.	W	X		
Carex lurida Wahlenb.	W			
Carex mitchelliana M.A. Curtis	SE	X	X	
Carex stricta Lam.	W	X		
Carex tribuloides Wahlenb.	W	X		
Cyperus dentatus Torr.	N	X	X	G4 / S1
Dulichium arundinaceum (L.) Britt.	W	X		
Eleocharis acicularis (L.) Roemer & J.A. Schultes	W	X		
Eleocharis melanocarpa Torr.	CP	X	X	G4 / S2
Eleocharis robbinsii Oakes	CP	X	X	G4G5 / S1
Eleocharis smallii Britt	N	X		
Eleocharis tenuis (Willd.) J.A. Schultes	W			
Eriophorum virginicum L.	N	X		
Fimbristylis autumnalis (L.) Roemer & J.A. Schultes	W	X		
Rhynchospora capitellata (Michx.) Vahl	W	X		
Rhynchospora gracilenta Gray	CP	X	X	
Scirpus cyperinus (L.) Kunth	W	X		
Scirpus subterminalis Torr.	N	X	X	G4G5 / S1S2
Scirpus torreyi Olney	N	X	X	G5? / S1
Scleria muehlenbergii Steud.	SE		X	
ERIOCAULACEAE				
Eriocaulon aquaticum (Hill) Druce	N	X	X	G5 / S1
HAEMODORACEAE				
Lachnanthes caroliana (Lam.) Dandy	CP	X	X	G4 / SH
IRIDACEAE				
Iris versicolor L.	N			
Iris virginica L.	W			
JUNCACEAE				
Juncus acuminatus Michx.	W	X		
Juncus brachycephalus (Engelm.) Buch.	N		X	G5 / S2
Juncus canadensis J. Gay *ex* Laharpe	W	X		
Juncus debilis Gray	CP	X	X	
Juncus dichotomus Ell.	SE	X		
Juncus effusus L.	W	X		
Juncus scirpoides Lam.	SE	X		
Juncus tenuis Willd.	W	X		

Taxon	Distributional Status	Pond Taxa	Outlier	Rarity Status
LEMNACEAE				
Lemna sp.	U	X		
LILIACEAE				
Aletris farinosa L.	W			
Amianthium muscitoxicum (Walt.) Gray	W			
Chamaelirium luteum (L.) Gray	SE			
Clintonia umbellulata (Michx.) Morong	A			
Helonias bullata L.	CP/A		X	G3 /S2S3 / LT / LE
Lilium canadense ssp. *editorum* (Fern.) Wherry	A			
Lilium superbum L.	SE			
Maianthemum canadense Desf.	N			
Medeola virginiana L.	W			
Melanthium parviflorum (Michx.) S. Wats.	A			
Uvularia puberula Michx. var. *puberula*	A			
Uvularia sessilifolia L.	W			
ORCHIDACEAE				
Arethusa bulbosa L.	N	X	X	G4 / S1
Calopogon tuberosus (L.) B.S.P.	W	X		G5T? /S2
Malaxis unifolia Michx.	W	X		
Platanthera ciliaris (L.) Lindl.	W			
Platanthera clavellata (Michx.) Luer	W	X		
Platanthera lacera (Michx.) G. Don	W			
Pogonia ophioglossoides (L.) Ker-Gawl.	W	X		
POACEAE				
Agrostis perennans (Walt.) Tuckerman	W	X		
Andropogon virginicus L.	W	X		
Aristida dichotoma Michx.	W	X		
Brachyelytrum erectum (Schreb. ex Spreng.) Beauv.	W			
Calamagrostis coarctata (Torr.) Eat.	SE			
Cinna arundinacea L.	W			
Dichanthelium acuminatum (Sw.) Gould & C.A. Clark	W	X		
Dichanthelium longiligulatum/spretum	U	X		
Dichanthelium sp.	U	X		
Digitaria filiformis (L.) Koel.	W	X		
Glyceria acutiflora Torr.	N	X		
Glyceria canadensis (Michx.) Trin.	N	X		
Glyceria melicaria (Michx.) F.T. Hubbard	A			
Glyceria obtusa (Muhl.) Trin.	CP	X	X	
Glyceria septentrionalis A.S. Hitchc.	W	X		
Glyceria striata (Lam.) A.S. Hitchc.	W			
Leersia oryzoides (L.) Sw.	W	X		
Panicum hemitomon J.A. Schultes	CP	X	X	G5? / S2
Panicum philadelphicum Bernh. *ex* Trin.	W	X		
Panicum rigidulum Bosc *ex* Nees var. *pubescens* (Vasey) Lelong	SE	X	X	
Panicum rigidulum Bosc *ex* Nees var. *rigidulum*	W	X		
Panicum verrucosum Muhl.	SE	X	X	

Taxon	Distributional Status	Pond Taxa	Outlier	Rarity Status
Panicum virgatum L. var. *virgatum* (incl. var. *cubense*)	W	X		
Paspalum laeve Michx.	SE	X		
Schizachyrium scoparium (Michx.) Nash	W	X		
Sorghastrum nutans (L.) Nash	W	X		
Torreyochloa pallida (Torr.) Church	N	X	X	
POTAMOGETONACEAE				
Potamogeton oakesianus J.W. Robbins	N	X	X	G4 / S2
Potamogeton sp.	U	X		
SMILACACEAE				
Smilax glauca Walt.	SE	X		
Smilax herbacea L.	W	X		
Smilax rotundifolia L.	W	X		
SPARGANIACEAE				
Sparganium eurycarpum Engelm. *ex* Gray	N		X	
Sparganium sp.	U			
XYRIDACEAE				
Xyris torta Sm.	W	X	X	
Dicotyledoneae				
ACERACEAE				
Acer rubrum L.	W	X		
APIACEAE				
Hydrocotyle americana L.	N			
Oxypolis rigidior (L.) Raf.	W			
APOCYNACEAE				
Apocynum cannabinum L.	W	X		
AQUIFOLIACEAE				
Ilex verticillata (L.) Gray	W	X		
ARALIACEAE				
Aralia nudicaulis L.	N			
ASCLEPIADACEAE				
Asclepias incarnata L.	W			
ASTERACEAE				
Aster acuminatus Michx.	N			
Aster dumosus L.	W	X		
Aster umbellatus P. Mill.	N			
Bidens cernua L.	W	X		
Bidens discoidea (Torr. & Gray) Britt.	W	X	X	
Bidens frondosa L.	W	X		
Boltonia asteroides (L.) L' Her. var. *asteroides*	CP	X	X	
Erechtites hieraciifolia (L.) Raf. *ex* DC.	W	X		
Eupatorium fistulosum Barratt	W			
Eupatorium pilosum Walt.	SE	X		
Eupatorium rotundifolium var. *ovatum*	SE	X		
Euthamia tenuifolia (Pursh) Nutt. var. *tenuifolia*	CP	X	X	
Helenium autumnale L.	W			
Helenium virginicum Blake	E	X		G2 /S2 / LT / LE
Rudbeckia fulgida var. *spathulata* (Michx.) Perdue	SE			
Senecio aureus L.	W			

Taxon	Distributional Status	Pond Taxa	Outlier	Rarity Status
BALSAMINACEAE				
Impatiens capensis Meerb.	W			
BETULACEAE				
Alnus serrulata (Ait.)Willd.	W			
Betula lenta L.	A			
BORAGINACEAE				
Myosotis laxa Lehm.	W			
BRASSICACEAE				
Cardamine bulbosa (Schreb. *ex* Muhl.) B.S.P.	W			
CABOMBACEAE				
Brasenia schreberi J.F. Gmel.	W	X		
CAMPANULACEAE				
Campanula aparinoides Pursh	W			
Lobelia cardinalis L.	W	X		
Lobelia siphilitica L.	W			
CAPRIFOLIACEAE				
Lonicera japonica Thunb.	EX			
Viburnum dentatum L.	W	X		
Viburnum nudum L. var. *cassinioides* (L.) Torr. & Gray	N			
Viburnum nudum L. var. *nudum*	SE		X	
CLUSIACEAE				
Hypericum boreale (Britt.) Bickn.	N	X		G5 / S2
Hypericum canadense L.	W			
Hypericum densiflorum Pursh	SE	X		
Hypericum gentianoides (L.) B.S.P.	W	X		
Hypericum gymnanthum Engelm. & Gray	SE	X	X	
Hypericum punctatum Lam.	W	X		
Triadenum virginicum (L.) Raf.	W	X	X	
Triadenum walteri (J.G. Gmel.) Gleason	SE	X	X	
CORNACEAE				
Cornus amomum P. Mill.	W	X		
CUSCUTACEAE				
Cuscuta compacta Juss. *ex* Choisy	W	X	X	
Cuscuta gronovii Willd. *ex* J.A. Schultes	W			
Cuscuta pentagona Engelm. var. *pentagona*	W	X		
Cuscuta polygonorum Engelm.	W	X	X	G5 / S2?
DROSERACEAE				
Drosera rotundifolia L.	N	X		
EBENACEAE				
Diospyros virginiana L.	SE	X		
ERICACEAE				
Gaultheria procumbens L.	N			
Gaylussacia baccata (Wangenh.) K. Koch	W	X		
Gaylussacia dumosa Torr. & Gray var. *bigeloviana* Fern.	CP	X	X	
Gaylussacia frondosa (L.) Torr. & Gray *ex* Torr.	CP		X	
Kalmia latifolia L.	W	X		
Lyonia ligustrina (L.) DC. var. *ligustrina*	SE	X		
Menziesia pilosa (Michx. *ex* Lam.) Juss. *ex* Pers.	A			

Taxon	Distributional Status	Pond Taxa	Outlier	Rarity Status
Rhododendron catawbiense Michx.	A			
Rhododendron periclymenoides (Michx.) Shinners	SE			
Rhododendron viscosum (L.) Torr.	SE			
Vaccinium corymbosum L.	W	X		
Vaccinium fuscatum Ait.	SE		X	
Vaccinium macrocarpon Ait.	N	X	X	G4 / S2
FABACEAE				
Apios americana Medik.	W			
Baptisia tinctoria (L.) R.Br. *ex* Ait. f.	W	X		
FAGACEAE				
Quercus alba L.	W			
Quercus palustris Muenchh.	MW	X		
GENTIANACEAE				
Bartonia paniculata (Michx.) Muhl.	SE	X	X	
Bartonia virginica (L.) B.S.P.	W	X		
Sabatia campanulata (L.) Torr.	SE	X	X	G5 / S2
HALORAGACEAE				
Proserpinaca palustris L.	W	X		
HAMAMELIDACEAE				
Hamamelis virginiana L.	W			
LAMIACEAE				
Lycopus sp.	U	X		
Mentha X *piperita* L	EX			
Mentha spicata L.	EX			
Pycnanthemum muticum (Michx.) Pers.	W			
Scutellaria integrifolia L.	SE	X		
Stachys hyssopifolia Michx.	CP	X	X	
Trichostema dichotomum L.	W	X		
LAURACEAE				
Lindera benzoin (L.) Blume	W			
LENTIBULARIACEAE				
Utricularia fibrosa Walt.	CP	X	X	G4G5 / S1
Utricularia geminiscapa Benj.	N	X	X	
Utricularia gibba L.	W	X		
Utricularia radiata Small	CP	X	X	
Utricularia subulata L.	SE	X	X	
Utricularia sp.	U	X		
LINACEAE				
Linum virginianum L.	W			
LYTHRACEAE				
Decodon verticillatus (L.) Ell.	W	X	X	
Rotala ramosior (L.) Koehne	W	X		
MAGNOLIACEAE				
Liriodendron tulipifera L.	W	X		
Magnolia acuminata (L.) L.	SE			
Magnolia virginiana L.	CP		X	
MALVACEAE				
Hibiscus moscheutos L. ssp. *moscheutos*	W	X		
MELASTOMATACEAE				
Rhexia mariana L. var. *mariana*	SE	X	X	

Taxon	Distributional Status	Pond Taxa	Outlier	Rarity Status
Rhexia virginica L.	W	X		
NYSSACEAE				
Nyssa sylvatica Marsh.	W	X		
NYMPHAEACEAE				
Nuphar lutea (L.) Sm. ssp. *advena* (Ait.) Kartesz & Gandhi	W	X		
OLEACEAE				
Chionanthus virginicus L.	SE			
ONAGRACEAE				
Ludwigia palustris (L.) Ell.	W	X		
Oenothera fruticosa L.	W			
POLYGALACEAE				
Polygala cruciata L.	W		X	
Polygala nuttallii Torr. & Gray	CP			
Polygala sanguinea L.	W			
POLYGONACEAE				
Polygonum hydropiper L.	EX	X		
Polygonum hydropiperoides Michx.	W	X		
Polygonum punctatum Ell.	W			
Polygonum sagittatum L.	W			
PRIMULACEAE				
Lysimachia ciliata L.	W	X		
Lysimachia hybrida Michx.	W	X		G5 / S2
Lysimachia quadriflora Sims	MW			G5? / S1
Lysimachia quadrifolia L.	W	X		
Lysimachia radicans Hook.	CP	X	X	G4G5 / SH
Lysimachia terrestris (L.) B.S.P.	N	X		
Trientalis borealis Raf. ssp. *borealis*	N			
RANUNCULACEAE				
Aconitum uncinatum L.	SE			
Caltha palustris L. var. *palustris*	N			
Ranunculus hispidus var. *caricetorum* (Greene) T. Duncan	N			
Thalictrum pubescens Pursh	W			
Trautvetteria caroliniensis (Walt.) Vail var. *caroliniensis*	SE			
ROSACEAE				
Amelanchier sp.	U			
Aronia arbutifolia (L.) Pers.	W	X		
Aronia melanocarpa (Michx.) Ell.	W			
Filipendula rubra (Hill) B.L. Robins.	MW			G4G5 / S2
Physocarpus opulifolius (L.) Maxim	N			
Rosa palustris Marsh.	W	X		
Rubus allegheniensis Porter	N			
Rubus hispidus L.	N			
Spiraea tomentosa L.	W	X		
RUBIACEAE				
Cephalanthus occidentalis L.	W	X		
Diodia teres Walt.	W	X		
Galium asprellum Michx.	N			

Taxon	Distributional Status	Pond Taxa	Outlier	Rarity Status
Galium tinctorium (L.) Scop.	W	X		
Galium sp.	U	X		
Mitchella repens L.	W			
SALICACEAE				
Salix humilis var. *tristis* (Ait.) Griggs	W	X		
SAXIFRAGACEAE				
Parnassia asarifolia Vent.	SE			
Parnassia grandifolia DC.	SE			G3G4 / S2
Saxifraga pensylvanica L.	N			
SCROPHULARIACEAE				
Agalinis purpurea (L.) Pennell	W			
Agalinis sp.	U			
Chelone glabra L.	W			
Mimulus ringens L.	W			
Pedicularis lanceolata Michx.	MW			
Veronica scutellata L.	N			G5 / S1
VIOLACEAE				
Viola cucullata Ait.	N			
Viola lanceolata L. ssp. *lanceolata*	N	X	X	
Viola primulifolia L.	SE	X		
VISCACEAE				
Phoradendron leucarpum (Raf.) Reveal & M.C. Johnston	SE	X		
VITACEAE				
Parthenocissus quinquefolia (L.) Planch. var. *quinquefolia*	W	X		

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Factors Controlling the Distribution and Abundance of the Narrow Endemic, *Helenium virginicum* (Asteraceae): Antiherbivore Defense?

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INTRODUCTION

Helenium virginicum Blake, the Virginia sneezeweed, is a perennial herbaceous member of the Asteraceae that is globally endemic to about 22 sinkhole ponds in Augusta and Rockingham Counties, Virginia (Knox, 1995; Van Alstine, 1996). The state of Virginia lists the species as Endangered (Porter & Wieboldt, 1991), and the U.S. Fish and Wildlife Service has recently listed the plant as a Threatened species under the U.S. Endangered Species Act (U.S. Fish and Wildlife Service, 1998).

The narrow endemism of *Helenium virginicum* seems to reflect its limitation to rare sites where competition with other species has been reduced by an unusual combination of stressful edaphic and hydrologic conditions (Knox, 1997). The clay soils at the sinkhole ponds where this species grows have a low pH, averaging 4.5, low levels of B, Ca, K, Mg, and P, and high levels of Al and As. The combination of low pH and high Al is the most important edaphic condition that limits the agricultural use of acid soils worldwide (Barinaga, 1997; Fuente et al., 1997), and is well known to impair uptake of the required macronutrients Ca, Mg, and K (Foy, 1974; Taylor, 1988).

Growing conditions in the sinkhole ponds inhabited by *H. virginicum* are made more stressful by dramatic seasonal changes in water depth (Fig. 1), with months of continuous flooding in cooler seasons alternating with periods of drawdown, when the basins lack any standing water, during warmer times of the year. Year-to-year variation in the duration of flooding may be great (Fig. 1); long periods of inundation have been associated with precipitous reductions in one population of *H. virginicum* (Fig. 2) intensively studied for 12 years at Kennedy Mountain Meadow (Knox, 1997; J. S. Knox, unpublished data). In other species, risk of extinction has been found to increase with increasing stochasticity of the environment and increasing variability of population size (Goodman, 1987; Pimm et al., 1988; Menges, 1991). It is not surprising then, that the Kennedy Mountain Meadow population has twice crashed after unusually lengthy periods of inundation that lasted for 16 and 20 months, in 1989 – 90, and 1995 - 97, respectively. Each time that extinction of extant plants has occurred, recruitment from a seed bank regenerated the population within one month of drawdown. In each case, local extinction was associated with heavy growth of floating aquatic vegetation.

Evidence suggests that these local extinctions might be explained in part by the shade intolerance of *H. virginicum*. Knox (1997) found that distribution of *H. virginicum* plants within sinkhole basins reflected shade intolerance of the species. At sites surrounded by tall forest with a relatively dense canopy, plants were absent from the south side of the basins where shade is greatest. Knox (1997) observed that deeper sinkhole ponds tended to have *H. virginicum* plants distributed in a belt, beyond the shade of dense vegetation near the shoreline, but not too deep to experience too much shade from the water column during the winter period of inundation. Knox (1997) found that the patterns of natural recruitment and the survival of transplants at Kennedy Mountain Meadow also suggested that *H. virginicum* is shade intolerant. Also, viable seeds that have broken dormancy do not germinate under favorable temperatures when the seeds are in the dark or under a standing column of water that contains green plants (J. J. W. Harvey and J. S. Knox, unpublished data). The plant grows year round, as is evident from the more narrow leaves produced during winter inundation (J. S. Knox, personal observation). We hypothesize that local extinctions occurred after long-term inundation because *H. virginicum* plants growing on the bottom of the basin were shaded below their light compensation point by

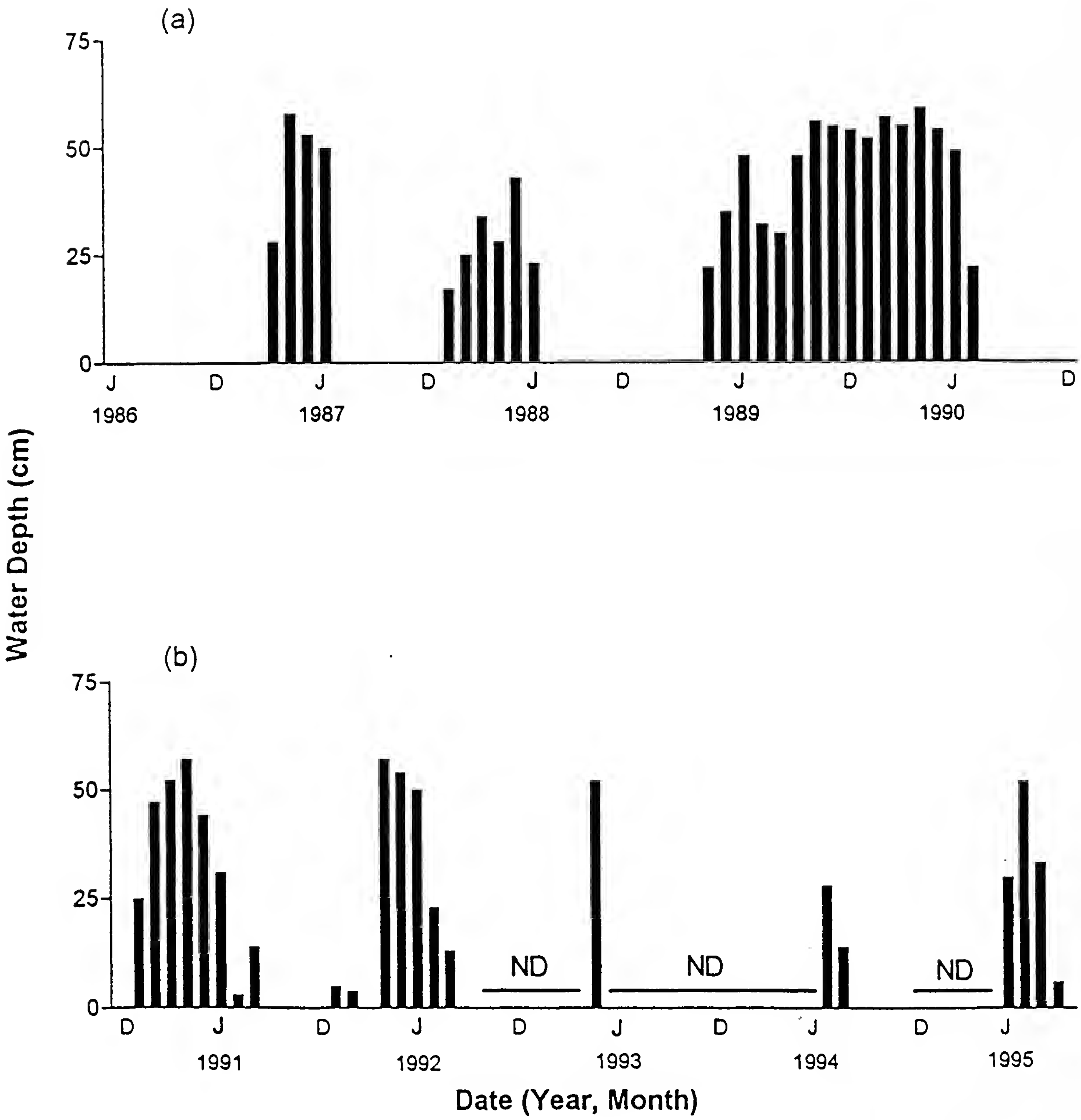

Fig. 1. Water depth (cm) measured monthly at the center (nearly the deepest point) at Kennedy Mountain Meadow. D is December; J is June; ND indicates no data collected.

floating aquatic vegetation.

Another factor that may make *H. virginicum* vulnerable to local extinction, and thus contribute to its narrow endemism, is the plant's sporophytic self-incompatible breeding system (Messmore & Knox, 1997). Successful seed production requires pollen with a different mating phenotype than is present on the stigma. Computer simulations (Byers & Meagher, 1992), as well as field studies (DeMauro, 1993) with other species, have revealed that this mating system increases the risk of local extinction in cases where population size falls to fewer than 50 flowering individuals. We think that for *H. virginicum*, the high year-to-year variability in hydroperiod, with its dramatic impact on population size, in conjunction with self-incompatibility, has created a situation in which the risk of local extinction is high and the probability of establishing a new population is low.

The largest and densest populations of *H. virginicum* occur at sites that have been disturbed by human activities such as mowing, grazing, and cutting trees. During a

period of population expansion in 1987, Knox (unpublished data) found densities of over 400 plants/m^2 at one sinkhole pond that had been disturbed by mowing, in comparison to densities up to 83 plants/m^2 at an especially dense area of an undisturbed site that same year. Knox (1997) speculated that the factors responsible for the much greater densities of *H. virginicum* at disturbed sites may have been activities that reduced the cover of competing plants, by trees having been cut, and the sites having been mowed and grazed. Knox (1997) called for future study of the impact of tree cutting, mowing, and grazing on *H. virginicum*, suggesting that this information could be useful for management of the species.

We suspect that *H. virginicum* may be unpalatable to herbivores; that grazing herbivores may selectively reduce the biomass of co-occurring plant species, thus reducing competition for light between the rare plant and its associates. This hypothesis seems plausible given that other species of *Helenium* are known to be toxic and unpalatable to vertebrate (Hesker, 1982; Anderson et al., 1983) and invertebrate (Arnason et al., 1987) animals. The toxicity of *Helenium* (Anderson et al., 1986; Arnason et al., 1987) and other plant genera (Burnett et al., 1977) has been associated with sesquiterpene lactones. Since *H. virginicum* is known to contain a specific sesquiterpene lactone, Virginolide, (Herz & Santhanam, 1967), and handling the plant leaves a bitter residue on the hands (J. Knox, personal observation), we suspect that *H. virginicum* may be unpalatable to generalist herbivores.

To test this hypothesis, we established a common garden study site where native vertebrate herbivores were known to be common, and planted large numbers of *H. virginicum* in close association with large numbers of an attractant plant species palatable to those herbivores. We sought evidence of selective avoidance of *H. virginicum* by herbivorous animals that fed on adjacent attractant

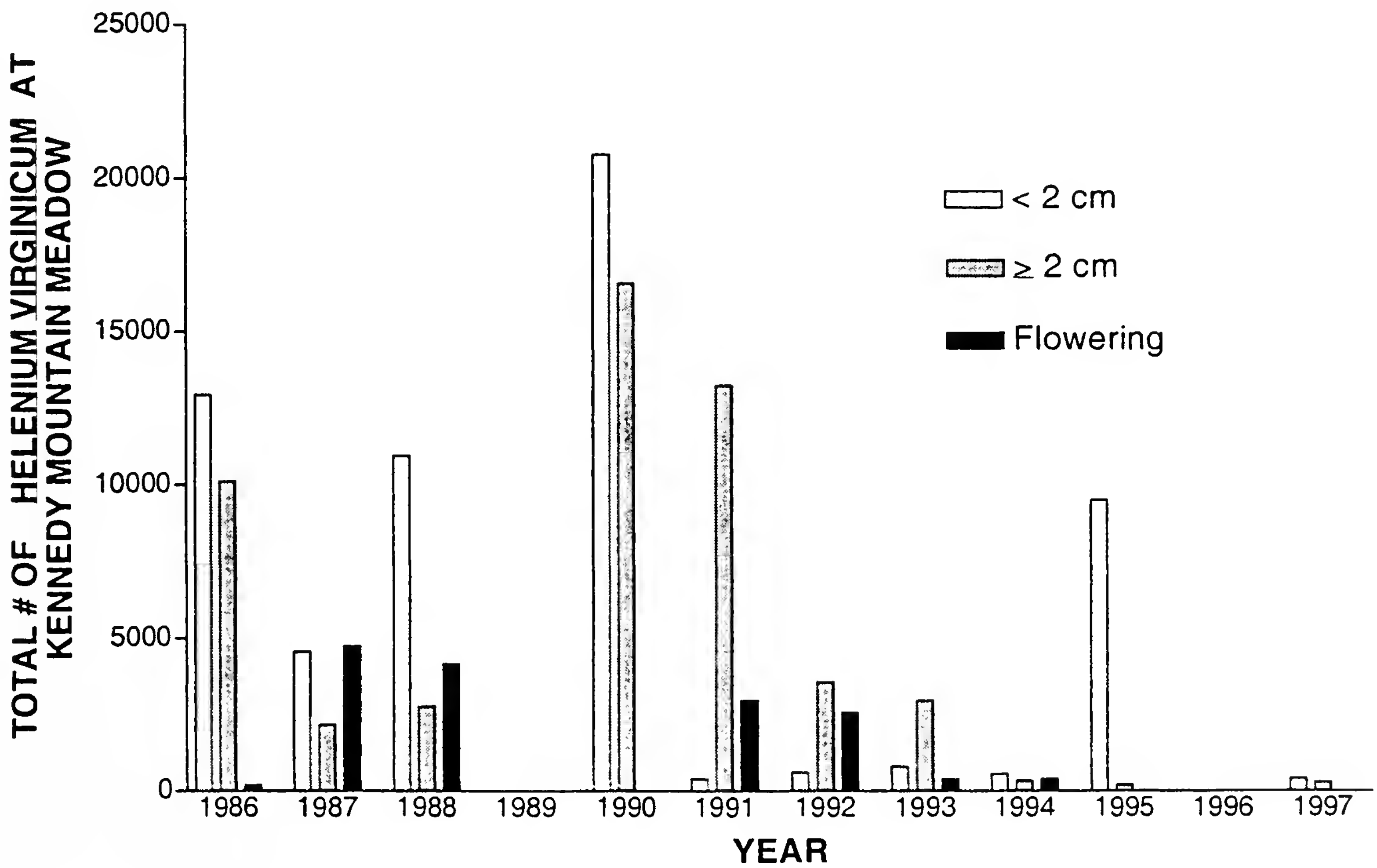

Fig. 2. Total number of *Helenium virginicum* plants growing within the 1 ha basin of Kennedy Mountain Meadow by stage class, censused in the fall of each year. Flowering refers to plants that flowered that season; < 2 cm refers to the length of the longest rosette leaf on plants that did not flower; ≥ 2 cm refers to the longest rosette leaf on plants that did not flower. Numbers are estimates made by extrapolating from annual census data taken at 53 permanent quadrats, except for 1994 and 1997, when total counts of all plants in the basin were made.

plants. We reasoned that if substantial herbivory of the attractant plant occurred, while interspersed with large numbers of *H. virginicum*, and the rare plant experienced little or no herbivory, we could infer that *H. virginicum* is unpalatable to herbivores. We were also interested to learn if *H. virginicum* would reduce the extent of herbivory on the attractant plant by comparing herbivory of attractant plants when grown in monoculture with those grown interspersed with *H. virginicum*. Such repellent plants have been described in other taxa (Atsatt & O'Dowd, 1976).

MATERIALS AND METHODS

In May 1998, we established a common garden in the center of an old field of approximately 0.5 ha on the campus of Washington and Lee University, Rockbridge County, Virginia. This site was chosen because we had often observed native herbivores (whitetailed deer, *Odocoileus virginiana*; cottontail rabbit, *Sylvilagus floridanus*; and woodchuck, *Marmota monax*) in the field. We tilled a 15 m X 15 m plot and divided it into sixteen 2 m X 2 m quadrats arranged in a 4 X 4 block design. Quadrats were separated by a 1 m wide walkway that ran among them; a tilled zone of 2 m bounded the study plot. Between 22 May and 3 June 1998, we planted the quadrats with four replicates of each of the following four treatments. The control treatment (#1) contained 15 bean (*Phaseolus vulgaris*) plants and 15 *H. virginicum*, alternating by species, with a wire fence surrounding the quadrat to exclude large vertebrate herbivores. The fence was 1.25 m tall, had 2.5 cm X 2.5 cm mesh to a height of 30 cm, and 5 cm X 7.5 cm mesh above. The other three treatments were left unfenced so that vertebrate herbivores could have access to them. Treatment #2 was planted with 30 *H. virginicum*. Treatment #3 was planted with 30 bean plants. Treatment #4 was planted with 15 *H. virginicum* alternating with 15 bean plants. Treatments were arranged within each row of the plot in a regular sequence, with treatments staggered from one row to the next. We arranged the 30 plants in each quadrat in a grid of six by five plants, alternating by species, and on approximately 30 cm centers.

The *H. virginicum* plants used in this experiment were a cohort of 240 adult plants that had been raised in a common garden individually in 12.7 cm pots of Hyponex potting soils from seeds collected at one natural site, and were more than three years old. The attractant plants used were Burpee™ Stringless Greenpod bush beans, planted in two cohorts. The first cohort of bean plants was composed of 240 adult plants that had been raised individually in 12.7 cm pots of Hyponex potting soil in a greenhouse. When the first cohort of bean plants showed symptoms of senescence on 5 June 1998, a second cohort of beans was started from seeds, by planting three bean seeds around each adult bean plant. On 17 June 1998, all first cohort bean plants were removed and the second cohort bean seedlings was thinned to leave one seedling where each first cohort bean plant had been. The treatment quadrats were weeded. We inspected the experimental plants nearly every day, but observed no evidence of herbivory until after the herbaceous vegetation in the surrounding old field was mowed on 6 July. On 8 July 1998, we began to observe substantial evidence of herbivory, and that evidence increased until 23 July, when we ended the experiment by harvesting the above ground biomass of each bean plant by cutting the stem at soil level. Each plant was placed separately in an aluminum pan and dried in an oven for three days at 95 C. Dried plants were placed at room temperature for one day, and then weighed to three decimal places on a top loading balance.

We tested for evidence of an herbivore repellent effect conferred by *H. virginicum* on the bean plants by comparing the above ground dry weight per bean plant under each treatment. We did this by using a Kruskal-Wallis nonparametric ANOVA to compare the median dry weight per bean plant for each treatment involving beans. The standard of $P < 0.05$ was used to judge significance.

RESULTS

When all beans were harvested and the experiment was concluded on 23 July, approximately 1/2 of all unfenced bean plants had been grazed with the top 10-25% of the bush removed. Many of the bean plants in all three treatments involving beans also showed evidence of insect herbivory, with leaf tissue having been partly removed between veins by Mexican Bean Beetles (*Epilachna varivestis*). None of the *H. virginicum* plants in any treatment had been grazed by vertebrate or invertebrate herbivores. We observed the hoofprints and feces of deer in the garden. The mean dry weight per bean plant $\pm$ SD was 5.04 ± 3.76 g for the fenced control treatment (#1) containing 15 beans and 15 *H. virginicum*, 5.18 ± 3.27 g for treatment #3, the monoculture of 30 beans, and 4.56 ± 2.45 g for the mix of 15 beans and 15 *H. virginicum*, unfenced. We found no significant difference (KW = 0.85; P = 0.65) in median above ground dry weight of bean plants in any paired comparisons.

DISCUSSION

Our experimental data suggest that *H. virginicum* is unpalatable to the common vertebrate herbivores present on the campus of Washington and Lee University. When the rare plant was grown interspersed with beans, it

showed no evidence of herbivory despite substantial vertebrate herbivory on beans. The vertebrate herbivore that selectively grazed the beans and avoided *H. virginicum* seems to have been the whitetailed deer, judging from the deer hoofprints and feces found in the garden at the time herbivory was observed. It would be desireable to test the unpalatability of the rare plant at sites where it grows naturally and where cattle graze, by comparing the demography of plants in fenced and unfenced quadrats. Should *H. virginicum* be found to benefit from selective grazing of co-occurring species, conservationists might use this information to manage the plant. Although the Mexican bean beetle was a common invertebrate herbivore on beans, it is an insect that is host limited to members of the legume family, and therefore not a broad generalist herbivore. Thus, its absence from *H. virginicum* cannot be considered a special example of plant unpalatability.

The lack of significant difference between median dry weight of bean plants that had experienced vertebrate herbivory (treatments #3 and #4) and those that had not (treatment #1, the fenced controls) is puzzling. It is possible that the bean plants that had been grazed experienced compensatory regrowth of new tissue, such as has been observed in other plants (reviewed in Lennartsson et al., 1998).

Based upon all the available evidence presented here, we suggest the following conservation efforts and management practices for *Helenium virginicum*:

1. Protect the hydrology of the sinkhole ponds.

2. Discourage growth of floating aquatic vegetation by avoiding eutrophication.

3. Encourage measures that open sites to sunlight.

4. Permit grazing and/or mowing of sites on a trial basis, making comparisons between the demography of plants in fenced control plots and grazed or mowed plots within sites.

5. Facilitate gene flow between populatons to reduce the risk of small population size to a plant with a self-incompatible breeding system.

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Dragonflies and Damselflies (Odonata) of the Shenandoah Valley Sinkhole Pond System and Vicinity, Augusta County, Virginia

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INTRODUCTION

The Big Levels area of the George Washington National Forest along the west flank of the Blue Ridge Mountains in southeastern Augusta County, Virginia contains a diverse assemblage of sinkhole ponds (Carr, 1940; Mohlenbrock, 1990; Buhlmann et al., 1999; Fleming & Van Alstine, 1999). These wetlands were formed through localized dissolution and collapse of karst terrain (dolomite and limestone) and subsequent deposition of alluvial materials from nearby mountain slopes. Whittecar & Duffy (1992) provide details of the latter process. Results of palynological research at two of the largest ponds in the region indicate that some of the ponds have been continuously present during the past 15,000 years (Craig, 1969). Soils of the region are strongly acidic and many of the sinkhole ponds are also acidic (Downey et al., 1999). This area will hereafter be referred to as the Shenandoah Valley sinkhole pond system following the terminology of Buhlmann et al. (1999). Whereas the diverse and interesting flora of these ponds has been well documented (Freer, 1933; Carr, 1937, 1938, 1940; Rawlinson & Carr, 1937; Harvill, 1973; Wieboldt et al., 1998; Fleming & Van Alstine, 1999), the fauna has received relatively little attention (e.g., Buhlmann & Hoffman, 1990). Elsewhere in this symposium volume, Mitchell & Buhlmann (1999) document the amphibian and reptile fauna of the region. There are no published accounts of the invertebrate fauna of the Shenandoah Valley sinkhole pond system. Since 1992, I have sampled the aquatic insect fauna of many of these ponds. The purpose of this paper is to summarize the results of my surveys for dragonflies and damselflies (Odonata), which comprised the primary focus of my efforts.

Previous surveys of the Odonata fauna of the Shenandoah Valley sinkhole pond system were limited. Carle (1982) recorded only two species (*Aeshna tuberculifera* and *Sympetrum rubicundulum*) during a visit to the Maple Flats ponds on 2 October 1977. Field notes and specimens of former Division of Natural Heritage (DNH) zoologist Kurt A. Buhlmann indicate that he recorded a total of seven species (five collected) from one of the Maple Flats ponds on 3 June 1990; he collected one of these same species at another pond on 2 June 1991. Carle (1982) listed dragonfly (Anisoptera) records from a site that he referred to as Shenandoah Pond in Augusta County, Virginia. This corresponds to the locality known as Green Pond in Carr (1938, 1940), Quarles Lake (Green Pond) in Harvill (1973), and Quarles Pond in Buhlmann et al. (1999) and this paper. Former DNH biologists Christopher A. Pague and Thomas J. Rawinski collected a few dragonflies at Green Pond on 1 June 1990 and 2 July 1991. This boggy mountain pond lies near the crest

Table 1. Number of Odonata species documented at the various ponds in the Shenandoah Valley study area.

	Damselflies	Dragonflies	Total
Maple Flats ponds	21	34	55
Loves Run Pond	10	20	30
Quarles Pond	-	18	-
Green Pond	5	13*	18
Total	21	39	60

*Excludes *Leucorrhinia frigida*

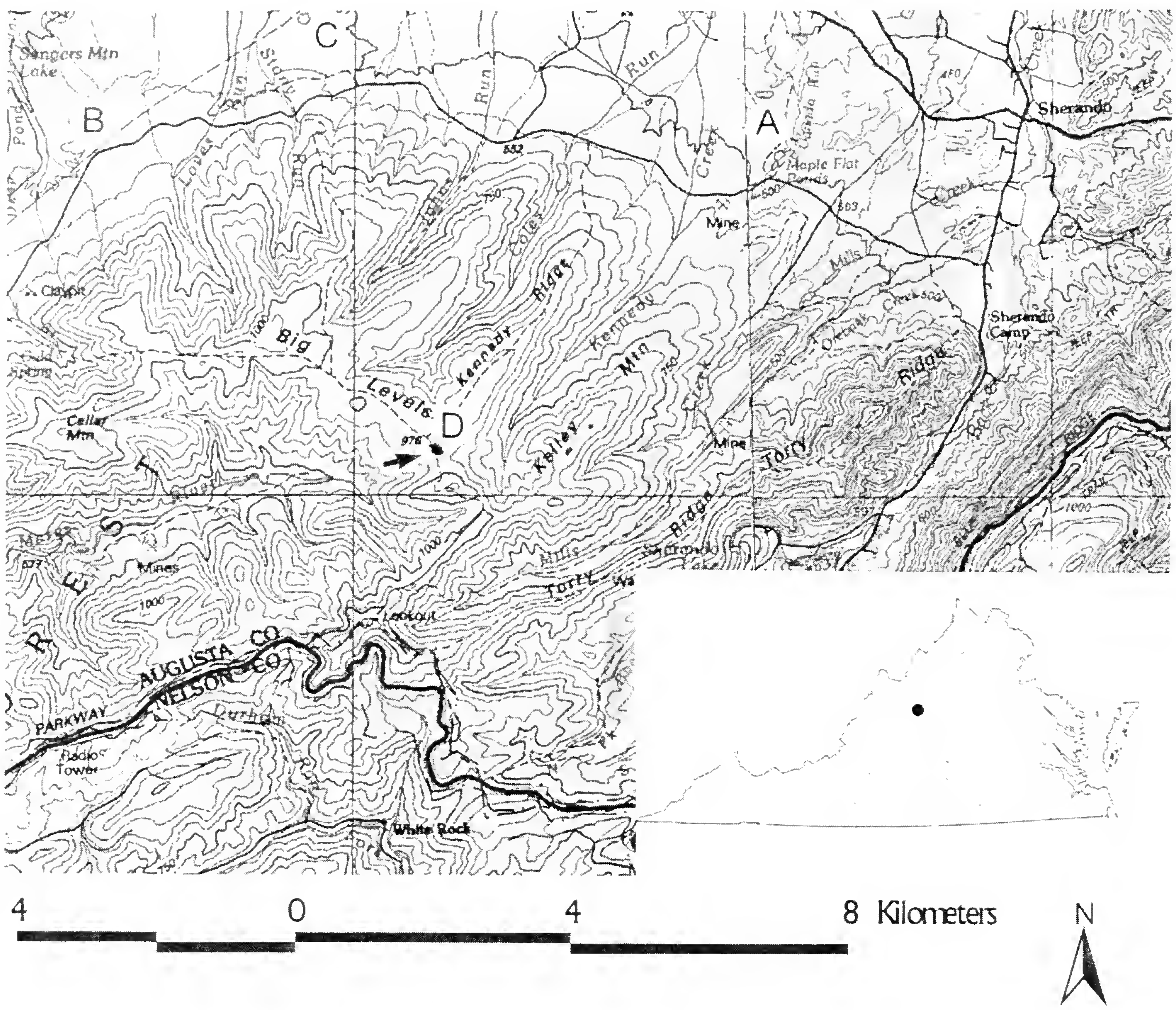

Fig. 1. Map of the study area showing primary survey areas (A = Maple Flats ponds; B = Loves Run Pond; C = Quarles Pond; D = Green Pond); inset indicates the location of the Shenandoah Valley sinkhole pond system within Virginia.

of Kennedy Ridge and is clearly labeled on the Big Levels U.S. Geological Survey topographic map; it is not equivalent to the Green Pond mentioned by Carr (1938, 1940) and Harvill (1973).

Elsewhere in the region, Surber's (1951) paper on the benthic fauna of the St. Marys River includes collection records of larval Odonata obtained from riffle habitats during 1935-37 that he identified only to the level of genus (i.e., *Aeshna*, *Lanthus*). His report of *Lanthus* sp. has been interpreted in recent years as *L. parvulus* by fisheries biologists from the George Washington National Forest, who now regard it as locally extirpated as a result of acid precipitation (M. Hudy, pers. comm.). This is a rare species in Virginia that has been confirmed only from Highland and Montgomery counties (Carle, 1991; see also Roble et al., 1997 regarding an apparent record from Page County). However, I believe it is more likely that Surber's record is referable to either *Stylogomphus albistylus* (formerly placed in *Lanthus*) or *L. vernalis* (described by Carle, 1980). I do not know if these collections are extant to potentially resolve this issue.

STUDY AREAS

My primary study area was the Maple Flats pond complex, which ranges in elevation from 470 to 485 m (1540-1590 ft). I surveyed the following five ponds most frequently: Maple Flats North, Maple Flats South, Oak,

Twin, and Spring. The first two ponds, hereafter referred to as North and South, are man-made impoundments of Canada Run that were created in the 1950s (Buhlmann et al., 1999). Both have water control structures and are stocked with game fish. The original habitat of these areas included boggy wetlands that bordered Canada Run (Buhlmann et al., 1999); the west and south margins of South Pond are still somewhat boggy. During my visits to the Maple Flats area, South Pond was usually maintained at a high water level, whereas North Pond was often very low. Spring Pond is the most unique pond in the complex; it is a permanent, spring-fed pond that is typically covered by a profuse growth of golden club (*Orontium aquaticum*) (Rawlinson & Carr, 1937; Carr, 1940; Buhlmann et al., 1999; Fleming & Van Alstine, 1999). The pond covers approximately 2.5 ha and its maximum depth is about 1 m. At least two species of fish inhabit Spring Pond (Buhlmann et al., 1999). Oak and Twin ponds are seasonally fluctuating sinkhole ponds that often dry completely or nearly so in summer or fall. At full capacity, Oak Pond has a surface area of approximately 0.8 ha and a maximum depth of ca. 3 m. Twin Pond consists of two adjacent sinkholes (= Twin Pond North and South of Buhlmann et al., 1999) that are connected when water levels are high; their combined surface area is approximately 1.2 ha and maximum depth is ca. 2 m.

My summary data for Twin Pond combines all observations made at both sinkholes. Oak and Twin ponds exemplify plant community type 1 of Fleming & Van Alstine (1999), which is not only the best represented community in the Shenandoah Valley sinkhole pond system, but also apparently endemic to this region and globally rare. The distinctive vegetation of this plant community is characterized by the presence of pin oak (*Quercus palustris*), panic grasses (*Panicum rigidulum* and *P. verrucosum*), and least spikerush (*Eleocharis acicularis*).

Two other wetlands in the Maple Flats area that I sampled less frequently were Split Level Pond (= Football Field Pond of Mohlenbrock [1990] and ponds 8 and 9 of Buhlmann et al. [1999]) and Horseshoe Swamp. The latter site consists of an extensive sedge marsh (ca. 1 ha; dominated by *Carex barrattii*, a rare species in Virginia) and an associated buttonbush (*Cephalanthus occidentalis*) pond area, a red maple (*Acer rubrum*)/highbush blueberry (*Vaccinium corymbosum*) acidic seepage swamp (ca. 1.5-2 ha) with an extensive carpet of *Sphagnum* moss and a small, semi-isolated boggy pond (also with some button-

Fig. 2. Photograph of Green Pond taken by the author on 18 June 1998. The dominant vegetation in the foreground is water sedge (*Carex aquatilis*) and three-way sedge (*Dulichium arundinaceum*). The former species is a northern disjunct, known in Virginia only from this site.

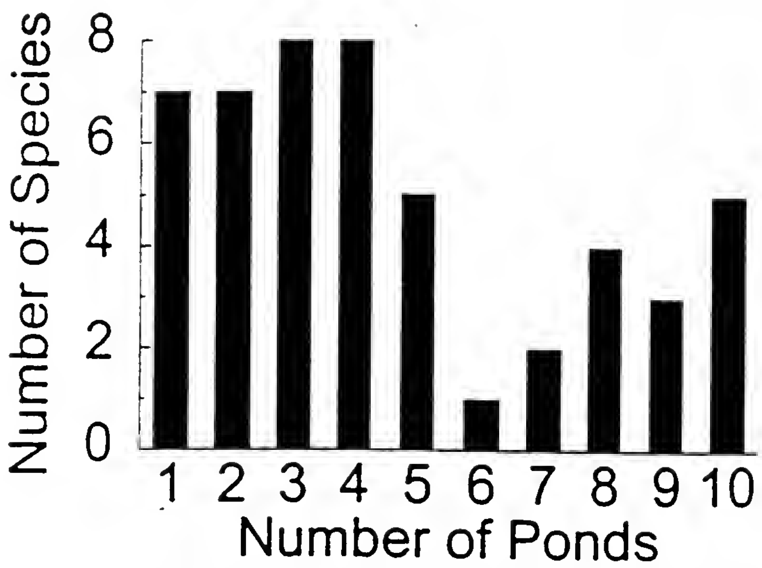

Fig. 3. Frequency of occurrence of Odonata species at study ponds (n = 11) in the Maple Flats complex.

bush). Fleming & Van Alstine (1999) identified the sedge marsh as a distinct plant community. For the purposes of data analysis and presentation, I divided Horseshoe Swamp into the following two sites: (1) sedge marsh and buttonbush pond; (2) seepage swamp and boggy pond. Split Level Pond covers about 1 ha and often dries completely in mid to late summer.

I made only 1-2 brief visits to ponds 2, 4, and 18 of Buhlmann et al. (1999). The former pond is also the site of Buhlmann's survey of 3 June 1990; his records are included in my summary tables. I did not survey for Odonata at Deep Pond (= pond 17 of Buhlmann et al., 1999), and never observed adult Odonata at Conical Pond (= pond 16 of Buhlmann et al., 1999) despite walking past this small, but deep sinkhole pond on numerous occasions. Detailed descriptions, photographs, and a map of all of the Maple Flats ponds are provided by Buhlmann et al. (1999); Fleming & Van Alstine (1999) contains a photograph of the buttonbush pond area at Horseshoe Swamp. Craig (1969) also provided a brief description of Spring Pond (reported as Hacks Pond), where he conducted a palynological study.

I conducted a total of six surveys for Odonata at the Loves Run pond complex, located ca. 11 km W of the Maple Flats pond complex (Fig. 1). All of my visits except the first were limited to a large sinkhole pond (ca. 1 ha; maximum depth ca. 2 m), hereafter referred to as the Loves Run Pond (= pond 21 of Buhlmann et al., 1999). The elevation of this permanent, heavily vegetated pond is approximately 550 m (1,820 ft). I also visited a nearby shallow, marshy pond (= pond 25 of Buhlmann et al., 1999) briefly on 20 June 1995. I did not visit any of the remaining smaller ponds in the Loves Run pond complex.

However, Anisoptera records from Quarles Pond (reported as Shenandoah Pond) that were summarized by Carle (1982) are also included in this paper. This shallow, privately owned pond is the largest pond in the Loves Run area (= pond 20 of Buhlmann et al., 1999); its elevation is approximately 506 m (1,660 ft) and maximum surface area between 3 and 4 ha. With one exception, the Quarles Pond records in Carle (1982) are based on voucher specimens collected during three surveys by Frank L. Carle (2 October 1977, 29 October 1978, and 13 June 1980) and one survey by Boris C. Kondratieff (17 July 1980). Sight records of *Anax longipes*, a large, distinctive dragonfly that is notoriously difficult to capture, were also obtained during the latter survey. No sight or collection records of damselflies (Zygoptera) from this pond were readily available for inclusion in this paper. Detailed descriptions and photographs of the three survey ponds in the Loves Run pond complex are provided by Buhlmann et al. (1999). Craig (1969) provides palynological data for Quarles Pond.

My final survey site was Green Pond (Fig. 2), a small, isolated, boggy mountain (elevation 976 m or 3,203 ft) pond along Kennedy Ridge in the Big Levels area. Water levels of this pond fluctuate considerably as a result of precipitation; maximum depth is about 1 m. The forest opening in which the pond occurs covers <1 ha. The pond contains abundant *Sphagnum* moss and is dominated by graminoid vegetation, particularly water sedge (*Carex aquatilis*) and three-way sedge (*Dulichium arundinaceum*). Green Pond is the only known Virginia locality for *C. aquatilis*, a northern disjunct (Wieboldt et al., 1998); these authors also provide a brief description of the pond. A dense mat of cranberry (*Vaccinium macrocarpon*) is limited to one side of the pond.

Table 2. Typical breeding habitat of the Odonata species documented at the various study areas.

	Ponds	Seepages	Streams
Maple Flats			
All species	48	0	7
Breeders	46	0	2
Loves Run	29	1	0
Quarles Pond	18	0	0
Green Pond	18	0	0
Total	52	1	7

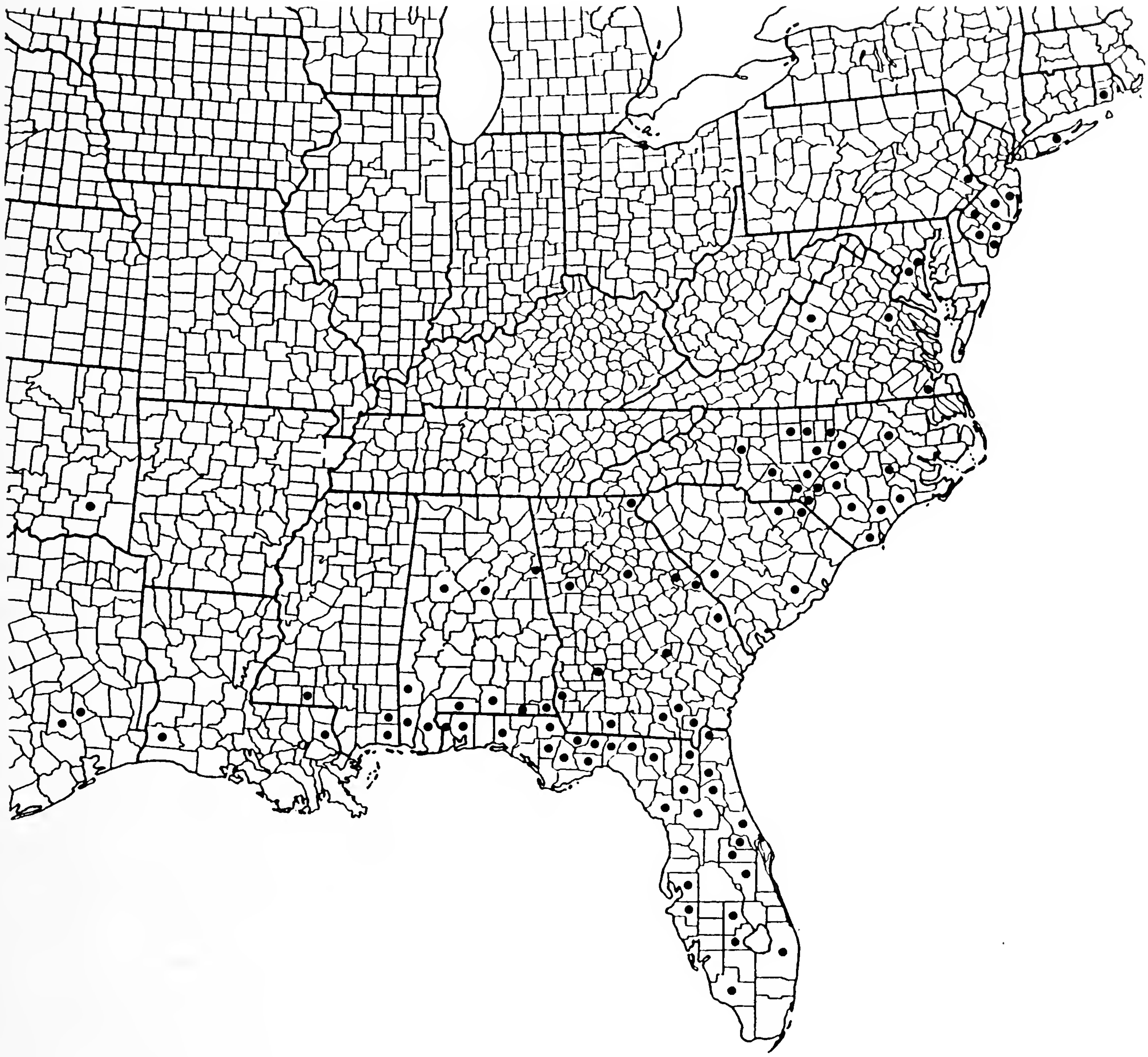

Fig. 4. Geographic distribution (by county) of the southern sprite (*Nehalennia integricollis*). See Appendix for data sources.

MATERIALS AND METHODS

I made 22 visits to the Maple Flats ponds between June 1992 and October 1998 during the flight season of adult Odonata; several ponds were visited on each trip, but only rarely did I visit all of the study ponds on the same date. I attempted to completely survey each pond that was visited for the presence of adult Odonata. The Loves Run Ponds were surveyed on six occasions (1995-98), with all but the first survey being devoted entirely to the largest sinkhole pond. I visited Green Pond three times (1992-98) during the months of June and July.

Most of my records are based on observations or collections of adult specimens; some larvae and exuviae were also collected. Voucher specimens were captured with standard insect nets for positive identification and documentation of the fauna of the Shenandoah Valley sinkhole pond system. Specimens were identified using Carle (1982), Carpenter (1991), Dunkle (1990, 1991), Needham & Westfall (1955), Walker (1952, 1953, 1958), Walker & Corbet (1975), and Westfall & May (1996). The majority of the specimens have been or will be deposited in the Virginia Museum of Natural History and the National Museum of Natural History, Smithsonian Institution (USNM).

Table 3. Local distribution of Odonata in the Shenandoah Valley sinkhole pond system and vicinity, Augusta County, Virginia.

Species	Maple Flats pond complex[a]													Other Study Ponds		
	S	N	Oak	Twin	Spr	SL	HS Marsh	HS Bog	2	4	18	Total Ponds	Trails, roads	Loves Run	Quarles[b]	Green
Calopteryx maculata[c]	x	x	-	-	x	x	x	-	-	-	-	5	x	-		-
Lestes congener	x	x	x	x	x	x	x	x	-	-	-	8	x	x		-
L. disjunctus australis	-	-	-	-	x	-	x	x	-	-	-	3	-	x		-
L. eurinus	-	-	x	-	-	x	-	x	-	-	-	3	-	x		x
L. forcipatus	x	x	x	x	x	x	x	x	-	x	x	10	-	x		x
L. rectangularis	x	x	-	-	x	x	-	-	-	-	-	4	-	x		-
L. vigilax	x	x	-	-	x	-	-	-	x	-	-	4	-	x		-
Argia fumipennis violacea	x	x	-	-	-	-	-	-	-	-	-	2	-	-		-
Chromagrion conditum	x	x	-	-	x	-	-	x	-	-	-	4	x	x		-
Enallagma aspersum	x	x	x	x	x	x	x	x	x	-	-	9	x	x		x
E. basidens	x	-	-	-	-	-	-	-	-	-	-	1	x	x		-
E. civile	x	-	-	x	x	-	-	-	-	-	-	3	-	-		-
E. divagans	x	x	-	-	-	-	-	-	-	-	-	2	-	-		-
E. doubledayi	-	x	-	-	-	-	-	-	-	-	-	1	-	-		-
E. exsulans	x	-	-	-	-	-	-	-	-	-	-	1	-	-		-
E. geminatum	x	-	-	-	-	-	-	-	-	-	-	1	-	-		-
E. signatum	x	x	-	x	-	x	-	-	-	-	-	4	-	-		-
Ischnura hastata	x	x	-	x	x	x	x	x	-	-	-	7	-	x		-
I. posita posita	x	x	x	x	x	x	x	x	-	-	-	8	-	x		x
I. verticalis	x	x	-	x	x	-	-	x	-	-	-	5	x	x		x
Nehalennia integricollis	x	-	-	-	-	-	-	-	-	-	-	1	x	-		-
Tachopteryx thoreyi	-	-	-	-	-	-	-	-	-	-	-	0	-	x	-	-
Aeshna constricta	-	-	-	-	-	-	-	-	-	-	-	0	-	-	x	-
A. mutata	-	-	-	-	-	-	-	-	-	-	-	0	-	x	x	-
A. tuberculifera	x	-	-	-	-	-	-	-	-	-	-	1	-	-	x	-
A. umbrosa umbrosa	x	x	-	x	-	-	-	-	-	-	-	3	-	x	-	x
Anax junius	x	x	x	x	x	x	x	x	x	x	-	10	-	x	x	x
A. longipes	-	-	-	-	-	-	x	x	-	-	-	2	-	x	x	-
Boyeria grafiana	-	-	-	-	-	-	-	-	-	-	-	0	x	-	-	-
B. vinosa	-	-	-	-	-	-	-	-	-	-	-	0	x	-	-	-
Epiaeschna heros	-	x	-	-	-	-	x	x	-	-	-	3	-	-	-	-
Gomphaeschna furcillata	-	x	-	-	-	-	x	-	-	-	-	2	-	-	-	-
Gomphus exilis	x	x	-	-	-	-	-	-	x	-	-	3	x	-	-	-
Cordulia shurtleffi	-	-	x	-	-	-	-	x	-	-	-	2	x	x	-	-
Epitheca cynosura	x	x	x	-	-	-	-	-	x	-	-	4	x	-	-	-
Somatochlora tenebrosa	x	x	x	x	x	-	-	-	-	-	-	5	x	-	-	-
Didymops transversa	-	-	-	-	-	-	-	-	-	-	-	0	x	-	-	-

Table 3 (continued).

Species	Maple Flats pond complex[a]													Other Study Ponds		
	S	N	Oak	Twin	Spr	SL	HS Marsh	HS Bog	2	4	18	Total Ponds	Trails, roads	Loves Run	Quarles[b]	Green
Celithemis elisa	x	x	x	x	x	x	x	x	x	-	-	9	x	x	x	x
C. fasciata	x	x	-	x	-	-	-	-	-	-	-	3	-	-	-	-
C. martha	-	-	-	-	x	-	-	-	-	-	-	1	-	-	-	-
C. verna	x	-	-	-	x	-	x	x	-	-	-	4	-	-	-	-
Erythemis simplicicollis	x	x	-	x	x	x	x	x	-	-	-	7	x	x	x	x
Erythrodiplax minuscula	x	-	-	-	x	-	x	-	-	-	-	3	-	-	-	-
Leucorrhinia intacta	-	x	x	-	x	-	x	x	-	-	-	5	x	x	x	x
Libellula auripennis	x	-	-	x	x	-	x	-	-	-	-	4	x	x	-	-
L. axilena	-	-	x	-	-	-	x	-	-	-	-	2	-	x	-	-
L. cyanea	x	x	-	-	x	-	x	x	-	-	-	5	x	x	x	x
L. deplanata	x	x	x	-	x	-	-	-	x	-	-	5	x	-	-	-
L. incesta	x	x	x	x	x	x	x	x	x	x	-	10	-	x	x	-
L. luctuosa	x	-	-	-	-	-	-	-	-	-	-	1	x	x	-	-
L. lydia	x	x	x	x	x	-	x	x	-	x	-	8	x	x	x	x
L. pulchella	-	-	x	-	-	-	x	x	x	-	-	4	-	x	x	-
L. semifasciata	x	x	x	-	-	-	x	x	x	-	-	6	x	x	x	x
Pachydiplax longipennis	x	x	x	x	x	x	x	x	-	x	-	9	-	x	x	x
Sympetrum rubicundulum	x	x	x	x	x	x	x	x	x	-	x	10	x	x	x	x
S. semicinctum	-	-	-	-	-	-	-	-	-	-	-	0	-	-	x	-
S. vicinum	x	x	x	x	x	-	x	x	x	-	-	8	-	x	x	x
Tramea carolina	x	x	x	x	x	x	x	x	x	x	-	10	-	x	x	x
T. lacerata	x	-	-	x	-	-	-	-	-	-	-	2	-	x	-	-
T. onusta	-	-	-	-	-	-	-	-	-	-	-	0	-	-	-	x
Number of surveys	14	14	9	9	8	3	6	6	3	1	1	-	-	6	4	3+
Total species	41	34	21	22	29	16	27	26	13	6	2	52[d]	3[e]	34	18[f]	18

[a] S = Maple Flats South Pond; N = Maple Flats North Pond; Spr = Spring Pond; SL = Split Level Pond; HS-Marsh = Horseshoe Swamp (portion containing sedge marsh and associated pond area only); and HS-Bog = Horseshoe Swamp (portion containing acidic seepage swamp and nearby boggy pond).

[b] No data available for Zygoptera.

[c] Found primarily along Canada Run in the Maple Flats area.

[d] Total species recorded at the Maple Flats pond complex.

[e] Total species recorded only along trails or roads in the Maple Flats area.

[f] Anisoptera only

RESULTS

I recorded a total of 55 species of Odonata in the Maple Flats area. The vast majority of these species are confirmed or probable breeders at this pond system. Five additional species were documented at the other study ponds in the Big Levels area, including two at Quarles Pond, one at Loves Run Pond, and one at Green Pond; the fifth species was recorded at both Quarles Pond and Loves Run Pond. The overall species diversity of the Odonata faunas at the various study sites is compared in Table 1. All but eight of the 60 species (87%) documented in the Shenandoah Valley sinkhole pond system study area are lentic breeders (Table 2). A detailed summary of the distribution of each species within the study area is provided in Table 3. The occurrence of a species at a particular pond does not necessarily mean that it breeds at that site; in some cases only a single individual of a given species was observed at the indicated pond. Some species were widely distributed in the study area, whereas others were found at only a few ponds (Fig. 3). The collective results of my surveys and records in Carle (1982) reveal that adult Odonata were present in the study area from late April through late October. Our observations produced record early or late flight dates for Virginia populations of 20 species of Odonata (Table 4); at least three of these (one early, two late) are apparently also rangewide record adult activity dates (see species accounts below).

Annotated Checklist

The following annotated checklist provides a brief summary of observations made on each species in the study area. Species known to breed at ponds in the study area are denoted by an asterisk (*). I define evidence of breeding as observations of one or more of the following: tandem pairs, ovipositing females, larvae, exuviae, or teneral adults. Suspected breeders are denoted by a plus sign (+); typically, I only observed patrolling males of these species. I am uncertain as to the local breeding status of one species (*Aeshna constricta*) that was recorded only at Quarles Pond by Carle (1982). Common names follow those recently adopted by the Dragonfly Society of the Americas (1996).

ZYGOPTERA (Damselflies)

Calopterygidae

Calopteryx maculata (Ebony Jewelwing)

This stream-breeding species is common along Canada Run in the Maple Flats area. I also observed several adults at the outlet to Spring Pond (an unnamed tributary of Canada Run), as well as 1-2 individuals at several other ponds in the Maple Flats sinkhole complex.

Coenagrionidae

**Argia fumipennis violacea* (Variable [Violet] Dancer)

This predominantly stream-breeding species was fairly common at South Pond, where it apparently breeds. A lone male was noted at North Pond. I also observed an adult male *Argia moesta* (Powdered Dancer) on 18 June 1998 along a forest road near Green Pond, but presume that it had strayed from the nearby St. Marys River (see map in Surber, 1951) and have omitted this species from the summary tables.

**Chromagrion conditum* (Aurora Damsel)

This is an early spring species that was abundant at South Pond, including nearby forest trails. I only observed a few individuals at the other Maple Flats ponds where it was recorded. I collected a mated pair at Loves Run Pond on 10 June 1996, my only record for that site.

**Enallagma aspersum* (Azure Bluet)

This is the most widespread bluet in the Maple Flats area, but I often did not find it there in large numbers (typically <20 adults per pond). My highest count was ca. 1000 at the Horseshoe Swamp buttonbush pond on 13 June 1997 (ca. 500 more at the nearby boggy pond on this date), followed by approximately 100 adults at Oak Pond during visits on 30 August 1996 and 13 June 1997. The maximum number seen at Green Pond was 250+ adults on 25 July 1997. In contrast, this species is very abundant at the Loves Run Pond, where I observed at least 3,000 (perhaps as many as 5,000) adults on 20 June 1995. This is comparable to the density observed at another sinkhole pond farther north in the Shenandoah Valley by Tim E. Vogt on 25 May 1991 (Roble, 1994). Adults typically perched on the stems of emergent vegetation, or in the case of Twin Pond, on the heads of *Eriocaulon aquaticum*, a state-rare pipewort. I found one dead female captured in a spider web, another near death (19 September), and one dead (9 September), both of the latter floating on the surface of Oak Pond.

**Enallagma basidens* (Double-striped Bluet)

I observed a few individuals at South Pond in the Maple Flats area on several occasions, as well as in a gas pipeline right-of-way near Loves Run Pond. I found one dead male floating on the surface of South Pond on 21 October. This small species has greatly expanded its range during the past half century (Cannings, 1989; Dunkle, 1990).

+*Enallagma civile* (Familiar Bluet)

I suspect this species, which is common throughout Virginia, breeds in low densities in the Maple Flats area, where I recorded it only a few times.

**Enallagma divagans* (Turquoise Bluet)

My records for this species are limited to 13 June 1997, when I observed 6 males and 2 mated pairs at North Pond and several more adults at South Pond.

Enallagma doubledayi (Atlantic Bluet)

I captured one male at North Pond on 9 August 1994 (Roble, 1994), my only encounter with this species in Virginia during the past seven field seasons. The only other published locality record for Virginia is from Blacksburg (Gloyd, 1951), although Carle (1988) tallied 11 records for the state. Westfall & May (1996) stated that *E. doubledayi* occurs primarily in the southeastern United States, although it ranges north to Cape Cod, Massachusetts (Carpenter, 1991). Donnelly (1961) reported this species from two sites in Maryland near the District of Columbia on the basis of collections made in 1900 and 1916, but there are no recent records of *E. doubledayi* from that state (R. L. Orr, pers. comm.). Resener (1970) reported this species from one county (Taylor) in Kentucky, but this record may be based on a previously misidentified, pre-1950 specimen (C. Cook, pers. comm.). Glotzhober (1995) stated that both Ohio specimen records were obtained on the same date in 1897. The Atlantic bluet has not been recorded from Tennessee or West Virginia (Westfall & May, 1996), but it is fairly common in eastern North Carolina (R. D. Cuyler, pers. comm.).

Enallagma exsulans (Stream Bluet)

A male of this stream-breeding species that I captured at South Pond on 27 July 1995 was undoubtedly a stray from a stream in the Big Levels area (but probably not Canada Run).

**Enallagma geminatum* (Skimming Bluet)

I found a few adults, including a mating pair, at South Pond on 18 August 1993, my only records for this species.

**Enallagma signatum* (Orange Bluet)

My observations indicate that the orange bluet is uncommon in the Maple Flats pond area.

**Ischnura hastata* (Citrine Forktail)

This tiny species is also uncommon in the Maple Flats pond area, being most abundant in the Horseshoe Swamp marsh habitat.

**Ischnura posita posita* (Fragile Forktail)

The fragile forktail is perhaps the most common damselfly in the study area.

**Ischnura verticalis* (Eastern Forktail)

Considering how common and widespread the eastern forktail is in western Virginia, it is surprisingly uncommon in the study area.

**Nehalennia integricollis* (Southern Sprite)

My discovery of a small population of this species at South Pond was unexpected. The southern sprite is primarily a Coastal Plain species, with scattered records from the Piedmont, which ranges from southern Rhode Island and Long Island, New York south to Florida and west to eastern Oklahoma and Texas (Fig. 4). In Virginia, it is known only from two other counties (Roble, 1994). The only other record of *N. integricollis* from the Blue Ridge region is from Rabun County, Georgia, where two males were collected by Minter J. Westfall, Jr. on 12 June 1972 at a pond near Satolah (specimens in the Florida State Collection of Arthropods; W. F. Mauffray, pers. comm.).

I found adults of the southern sprite only along the boggy western shoreline of South Pond (mostly concentrated in a 15 m section) and a nearby forest trail in several different years of this study. Dominant vegetation along the pond edge in the area of their greatest density was *Sphagnum* sp., *Eleocharis smallii, Dulichium arundinaceum,* and (less so) *Carex gynandra.* I observed a maximum of 75 adults on any one visit, usually including both mature and teneral individuals.

Lestidae

**Lestes congener* (Spotted Spreadwing)

This is a late summer and fall species that I encountered in low densities (typically < 25 adults) at several ponds in the Maple Flats area. It was most abundant at South Pond, where at least 125 adults were observed on 21 October 1994. My earliest record was 10 June.

**Lestes disjunctus australis* (Common Spreadwing)

This subspecies is very similar to *Lestes forcipatus* and therefore difficult to readily distinguish in the field (Walker, 1952). I found only a few adults at Loves Run Pond and the Maple Flats pond complex; it was not recorded at Green Pond.

**Lestes eurinus* (Amber-winged Spreadwing)

This northern species is most common at Loves Run Pond, being decidedly scarce at Maple Flats and Green

Table 4. Seasonal distribution of Odonata at the Shenandoah Valley sinkhole pond system and vicinity, Augusta County, Virginia.

Month	Apr.	May		June			July			Aug.			Sept.			Oct.			Early and Late Flight Dates
Species / Period[a]	3	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	* = Extreme date for Virginia[b]
Calopteryx maculata				x	x			x	x	x		x							10 June - 30 August
Lestes congener				x				x				x	x	x			x	x	10 June* - 21 October
L. disjunctus australis				x				x	x			x							10 June - 30 August
L. eurinus				x	x		x	x	x										10 June - 27 July
L. forcipatus					x	x	x	x	x	x	x	x		x	x			x	13 June - 21 October*
L. rectangularis						x	x	x		x	x	x	x		x				24 June - 26 September
L. vigilax				x	x			x	x	x	x	x	x		x			x	10 June - 21 October*
Argia fumipennis violacea			x		x		x	x	x		x		x	x					31 May - 19 September
Chromagrion conditum	x			x	x	x													29 April - 24 June
Enallagma aspersum			x	x	x	x	x	x	x		x	x	x	x	x				31 May - 26 September*
E. basidens					x			x			x							x	13 June - 21 October*
E. civile								x			x						x	x	13 July - 21 October*
E. divagans					x														13 June
E. doubledayi										x									9 August
E. exsulans									x										27 July
E. geminatum											x								18 August
E. signatum			x			x		x		x									31 May - 9 August
Ischnura hastata			x	x	x	x		x	x	x	x	x			x		x	x	31 May - 21 October
I. posita posita	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x		29 April - 13 October*
I. verticalis	x		x	x	x	x			x	x		x	x	x	x		x		29 April - 13 October*
Nehalennia integricollis							x	x	x	x	x								6 July - 18 August
Tachopteryx thoreyi					x														18 June
Aeshna constricta																x		x	2 October* - 29 October*
A. mutata				x	x														10 June - 20 June*
A. tuberculifera																x		x	2 October - 29 October*
A. umbrosa umbrosa									x		x	x			x				25 July - 26 September
Anax junius	x			x	x	x	x	x	x	x	x	x	x	x	x		x		29 April - 13 October
A. longipes				x	x			x	x										10 June - 27 July
Boyeria grafiana											x								18 August
B. vinosa										x	x								9 August - 18 August
Epiaeschna heros			x		x														31 May - 13 June
Gomphaeschna furcillata			x		x														31 May - 13 June*
Gomphus exilis				x	x			x											3 June - 13 July
Cordulia shurtleffi	x			x	x														29 April* - 20 June
Epitheca cynosura	x	x	x	x	x														29 April - 13 June
Somatochlora tenebrosa								x	x	x	x		x	x	x				13 July - 26 September
Didymops transversa	x				?														29 April (- 13 June ?)
Celithemis elisa		x	x	x	x	x		x	x	x	x	x	x		x				20 May - 26 September*
C. fasciata								x	x										13 July - 27 July
C. martha									x			x							27 July - 30 August
C. verna			x	x	x	x		x	x		x								31 May - 18 August*
Erythemis simplicicollis				x	x	x		x	x	x	x	x	x		x				10 June - 26 September
Erythrodiplax minuscula										x	x	x							9 August - 30 August
Leucorrhinia intacta	x			x	x	x			x										29 April* - 25 July*

Table 4 (continued).

Month	Apr.	May	June	July	Aug.	Sept.	Oct.	Early and Late Flight Dates
Species Period[a]	3	2 3	1 2 3	1 2 3	1 2 3	1 2 3	1 2 3	* = Extreme date for Virginia[b]
Libellula auripennis			x x	x x	x x			10 June - 30 August*
L. axilena			x	x x				13 June - 27 July
L. cyanea			x x x	x x	x			10 June - 5 August
L. deplanata	x	x	x x	x				29 April - 8 July*
L. incesta			x x	x x	x x x	x x		10 June - 26 September
L. luctuosa			x	x	x			20 June - 18 August
L. lydia	x		x x x	x x x	x x x	x		29 April - 9 September
L. pulchella			x x	x	x	x x		3 June - 20 September*
L. semifasciata		x	x x	x x x				31 May - 27 July
Pachydiplax longipennis			x x x	x x	x x x	x		10 June - 26 September
Sympetrum rubicundulum			x x	x x x	x x	x x x	x x x	20 June - 21 October
S. semicinctum							x	29 October*
S. vicinum				x	x x x	x x x	x x	25 July - 29 October
Tramea carolina		x	x x x	x x	x x x	x		31 May - 9 September
T. lacerata			x		x x			18 June - 30 August
T. onusta				x				2 July*

[a] 1 = 1st to 10th days of the month; 2 = 11th to 20th days; 3 = 21st day to the end of the month; no data for missing periods.

[b] Exceeds or equals early or late date reported by Carle (1982), Roble (1994), Roble & Hobson (1996) or Roble et al. (1997); see species accounts for more details.

Pond. I observed at least 300 adults at Loves Run Pond on 20 June 1995.

**Lestes forcipatus* (Sweetflag Spreadwing)

My observations indicate that this is the most common spreadwing in the Maple Flats pond complex. My highest counts (300+ adults) were obtained at Spring Pond on 18 August 1993 (including 40+ mated pairs) and 27 July 1995. On 18 June 1998, Paul Bedell and I observed Cedar Waxwings (*Bombycilla cedrorum*) preying on teneral spreadwings, presumably *L. forcipatus*, at Green Pond. On 27 July 1995, I observed a mature female *L. forcipatus* preying on a teneral fragile forktail (*Ischnura posita*). A male *L. forcipatus* was observed clasping a female *L. congener* at Twin Pond on 30 August 1996. Shortly before dusk on 19 September 1994, I collected what appeared to be a nearly dead mating pair of *L. forcipatus* from the surface of this same pond.

Westfall & May (1996) reported that the known flight period of *L. forcipatus* throughout its range extends from 4 April to 22 September. My latest record (as reported previously in Roble, 1994) was 21 October, when I found one female at Spring Pond. This species was common at that pond on 26 September of the same year.

**Lestes rectangularis* (Slender Spreadwing)

Only a few scattered individuals of this elongate species were found at Loves Run Pond and in the Maple Flats pond area.

**Lestes vigilax* (Swamp Spreadwing)

I encountered relatively few individuals of the swamp spreadwing during my surveys. This species was most common at Spring Pond (>100 adults observed on several dates), where I found it as late as 21 October.

ANISOPTERA (Dragonflies)

Petaluridae

Tachopteryx thoreyi (Gray Petaltail)

My only record for this large, primitive dragonfly that breeds in seepage habitats was an adult that I observed momentarily along a forest trail near Loves Run Pond on 18 June 1998. This species may breed in seeps near this pond as well as additional seeps near Spring Pond and Horseshoe Swamp, but I did not observe adults in these other areas and larval surveys were not conducted at any seepage habitats. This species was previously recorded

Table 5. Species diversity of Odonata in the Maple Flats ponds area and vicinity (Big Levels) as compared to the Odonata fauna of Virginia.

FAMILY	MAPLE FLATS	BIG LEVELS	VIRGINIA	PERCENT
Calopterygidae	1	1	7	14.3
Lestidae	6	6	10	60.0
Coenagrionidae	14	14	37	37.8
Total Zygoptera	21	21	54	38.9
Petaluridae	0	1	1	100.0
Aeshnidae	8	10	16	62.5
Gomphidae	1	1	39[a]	2.6
Cordulegastridae	0	0	5	0.0
Corduliidae	3	3	19	15.8
Macromiidae	1	1	5	20.0
Libellulidae	21	23	43[b]	53.5
Total Anisoptera	34	39	128	30.5
Total Odonata	55	60	182	33.0

[a]Excludes one reported but unconfirmed species
[b]Excludes two accidental species

from Augusta County by Carle (1982), who captured a female near the Calfpasture River about midway between West Augusta and Deerfield.

Aeshnidae

Aeshna constricta (Lance-tipped Darner)

Carle (1982) reported that he collected single males on 2 October 1977 and 29 October 1978 at Quarles Pond, one of only two known sites for this northern species in Virginia (Fig. 5). This darner ranges south to Kentucky and Tennessee, but there are no records for North Carolina (Trogdon, 1961; Resener, 1970; Huggins & Brigham, 1982; Bick, 1997; R. D. Cuyler, pers. comm.).

**Aeshna mutata* (Spatterdock Darner)

This spring and early summer species was recorded at both Loves Run Pond and Quarles Pond. I observed 4-6 adult males at the former site on 20 June 1995 (two collected), but saw only 1-2 on 10 June 1996 and none on 18 June 1998. The former record establishes a new late date for this species in Virginia, exceeding the date listed in Carle (1982, 1991) by a full week. Beatty & Beatty (1969) reported that females of this species preferentially oviposit in spatterdock (*Nuphar lutea* ssp. *advena*), which accounts for its recently coined common name. This aquatic plant is absent at Loves Run Pond, but Carr (1938, 1940) stated that it is dominant at Quarles Pond (reported as Green Pond). Carle (1982) indicated that he collected 35 adults (28 ♂, 7 ♀) and 25 exuviae of *A. mutata* at the latter site on 13 June 1980. The Quarles Pond population of this species is one of the largest known rangewide (F. L. Carle, pers. comm.). Carle (1991) recommended *A. mutata* for threatened status in Virginia, but it remains unprotected in the state. The spatterdock darner has been recorded from a total of seven sites in four Virginia counties (Fig. 5). It is widespread but very local in the northeastern and midwestern portions of the United States.

+*Aeshna tuberculifera* (Black-tipped Darner)

Carle (1982) reported that he collected adults at the Maple Flats ponds (= North and/or South Pond; F. L. Carle, pers. comm.) on 2 October 1977 (1♂, 1♀) and at Quarles Pond on 29 October 1978 (1♂). My only records of *A. tuberculifera* were two males that I captured at South Pond on 21 October 1994. This northern species may breed in the study area. Halverson (1984) reported that it has a 2-year life cycle in the mountains of Virginia; his study sites were small (5-15 m diameter), man-made, fishless ponds on the George Washington National Forest. This species has been recorded from a total of eight counties in Virginia (Fig. 5) and ranges south to western North Carolina (Cuyler, 1984). There are no records for Kentucky or Tennessee (Trogdon, 1961; Resener, 1970; Bick, 1997).

+*Aeshna umbrosa umbrosa* (Shadow Darner)

The shadow darner was recorded several times at the Maple Flats ponds, but only a few individuals were seen on each occasion. I suspect that it breeds in the area in low density. A lone male was observed at Loves Run Pond on 30 August 1996. The only individual of this species that I observed at Green Pond (25 July 1997) was an adult female that was apparently the subject of an attempted mating by a male *Anax junius*. I netted them as they were struggling in a sedge clump along the shoreline of this pond. Surber's (1951) report of *Aeshna* nymphs from the St. Marys River presumably refers to this species. Walker (1958) stated that, unlike most species of *Aeshna*, *A. umbrosa* prefers shady habitats and typically breeds in streams or ditches rather than lakes or ponds. However, Halverson (1984) documented this species breeding in small mountain ponds in Rockingham County, Virginia.

**Anax junius* (Common Green Darner)

This species is common in the Big Levels area, and was recorded at virtually every study pond. I observed a group of four males tumbling to the surface of Split Level

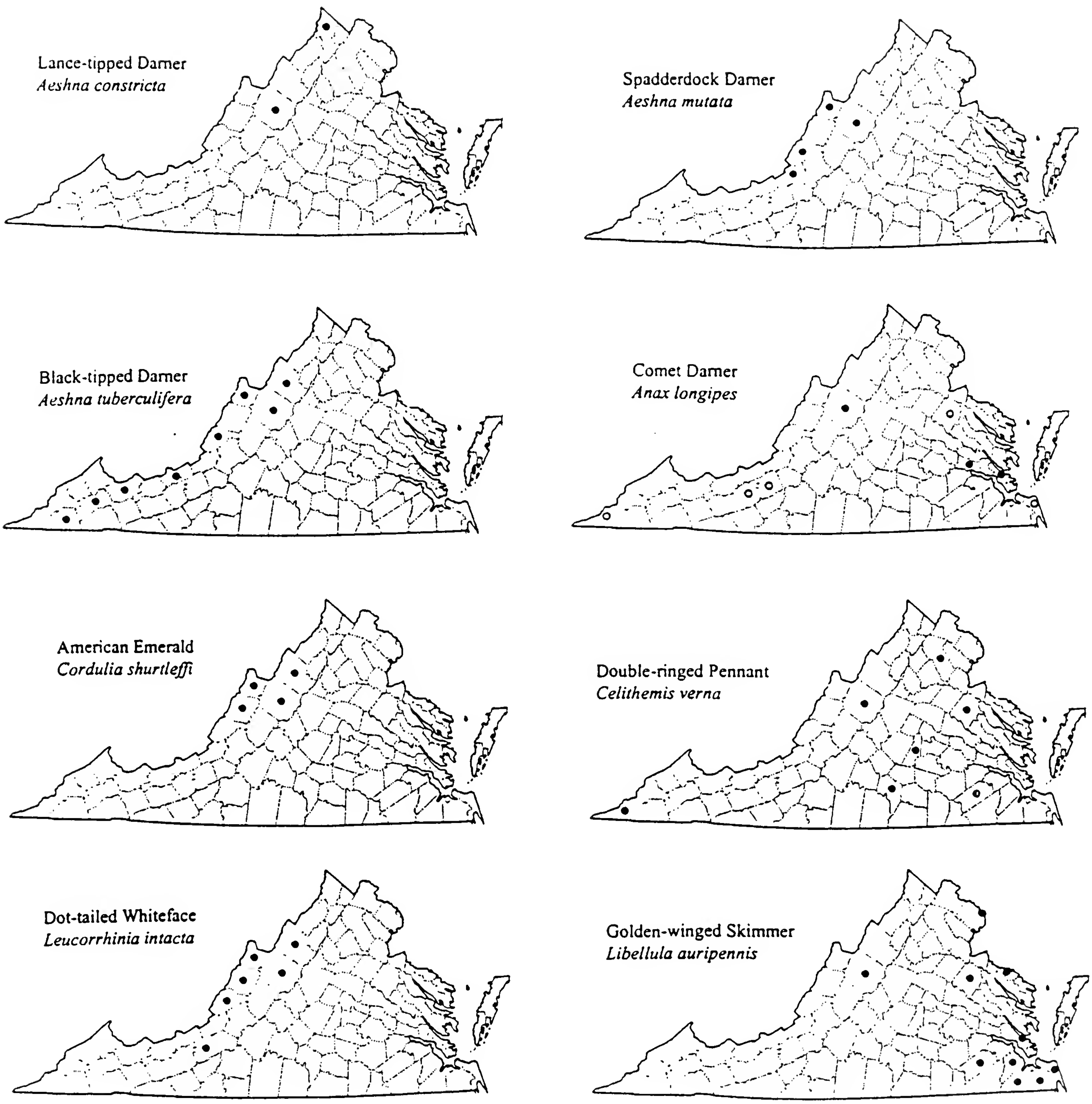

Fig. 5. Documented Virginia distribution (by county) for eight species of state-rare or uncommon dragonflies (Anisoptera) recorded in the Shenandoah Valley sinkhole pond system. Solid circles denote records supported by voucher specimens, half-filled circles signify photographic records, and open circles indicate records based solely on observations.

Pond at 1830 h on 13 July 1995, apparently as the result of a territorial skirmish. Exuviae were abundant at Loves Run Pond, particularly on the stems of highbush blueberry bushes that bordered the pond; they were found at heights of 0.2 to 2 m (most >1 m).

**Anax longipes* (Comet Darner)

Three males of this large, unmistakable dragonfly (males have bright red abdomens) were observed at Quarles Pond on 17 July 1980 by Boris C. Kondratieff (Carle, 1982). I observed up to 10 males during several June visits to Loves Run Pond (one collected); two were also seen at the nearby marshy pond on 20 June 1995. Single males were found on two occasions at Horseshoe Swamp. The comet darner has been recorded from only eight counties in Virginia (Fig. 5), mostly on the basis of sight records. The first records of this species from Pulaski and Montgomery counties are based on observations of single males made by C. Shay Garriock (pers. comm.) of the Virginia Department of Game and Inland Fisheries during 1997 (one date) and 1998 (two dates), respectively. Although *A. longipes* is not globally rare, this species is considered rare to uncommon in virtually all of the states throughout its range (e.g., Carle, 1979, 1989; Carpenter, 1991). It typically breeds in semipermanent, grassy ponds that lack fish (Dunkle, 1989).

Boyeria grafiana (Ocellated Darner)

This species typically inhabits rocky rivers and large streams. I captured a male at dusk on 18 August 1993 along Forest Service Road 42 (Coal Road) near South Pond. It probably breeds in the Big Levels area, but I did not attempt to locate any local populations.

Boyeria vinosa (Fawn Darner)

This is primarily a stream and river-dwelling species. Adults were seen at dusk along Forest Service Road 42 (Coal Road) near South Pond on several occasions. One adult was also found along a trail between North and South ponds on 9 August 1994. Like the preceding species, the fawn darner probably breeds in the Big Levels area, but I did not attempt to locate any local populations.

Epiaeschna heros (Swamp Darner)

I observed one adult of this large darner very briefly at North Pond on 31 May 1995. Two or three adults (1-2 ♂, 1♀) were also observed at Horseshoe Swamp on 13 June 1997. Halverson (1984) determined that *E. heros*

Table 6. Relative staus (in Virginia) of the Odonata species documented in the Shenandoah Valley sinkhole pond system and vicinity. Data are expressed as the number of species followed by the percentage of total species in each row.

	Rare (S1-S2)[a]	Uncommon (S3)	Common (S4-S5)
Maple Flats ponds			
All species	7 (13)	12 (22)	36 (65)
Breeders	7 (14)	9 (19)	32 (67)
Loves Run	4 (13)	6 (20)	20 (67)
Green Pond[b]	1 (6)	2 (12)	14 (82)
Quarles Pond[c]	5 (28)	0 (0)	13 (72)
Shenandoah Valley ponds[b] (total)	9 (15)	13 (22)	37 (63)

[a] Natural Heritage ranks (1-5 scale ranging from extremely rare to very common; based largely on the number of known and estimated populations in the state).

[b] Excludes *Leucorrhinia frigida* due to the uncertain origin of the historical specimen and *Tramea onusta* which is classified as a vagrant or accidental species in Virginia.

[c] Anisoptera only (data from Carle, 1982).

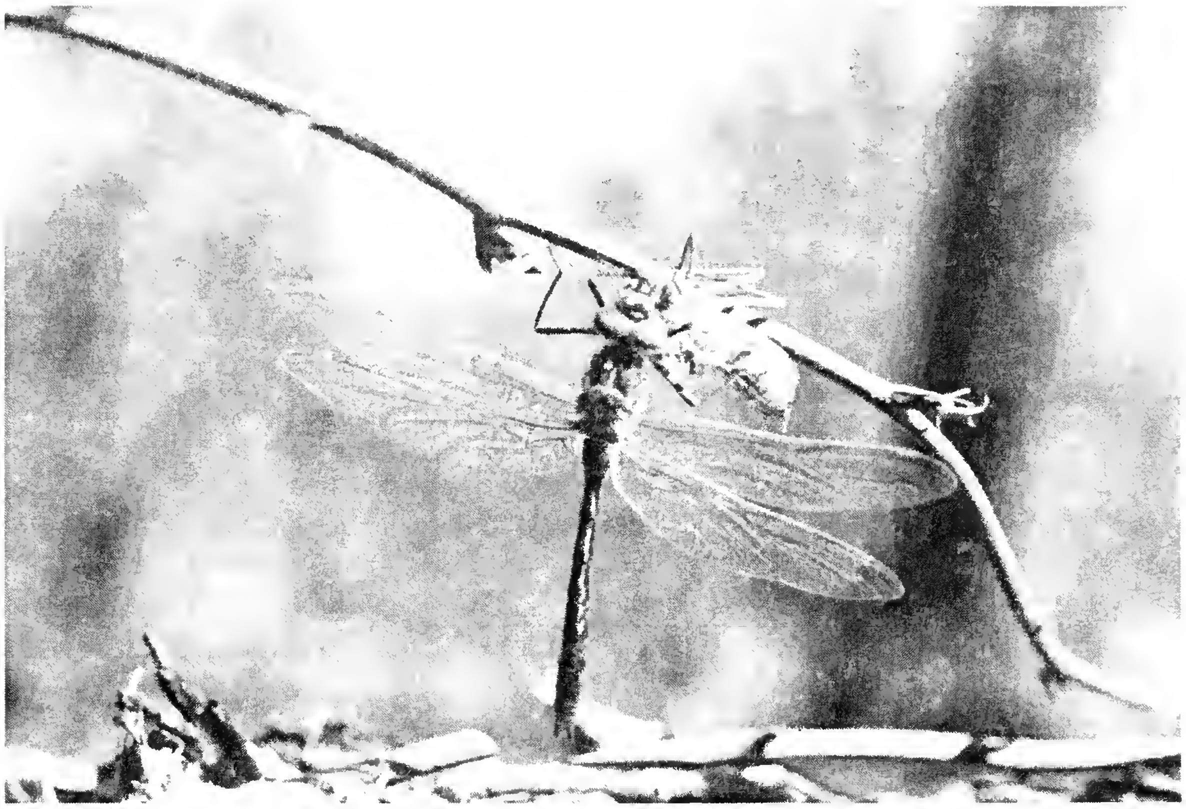

Fig. 6. Newly emerged adult male American emerald (*Cordulia shurtleffi*) beside its exuvia; photographed at Oak Pond on 29 April 1997 by the author.

Fig. 7. Adult male Martha's pennant (*Celithemis martha*); photographed on Cape Cod, Massachusetts by Blair Nikula.

bred during only one of four consecutive years (and at low densities) at a series of small mountain ponds on the George Washington National Forest in Rockingham County. This species may breed in the study area, but is most abundant in Coastal Plain swamps (e.g., Roble & Cuyler, in press).

+*Gomphaeschna furcillata* (Harlequin Darner)

Two adult females were collected at North Pond on 31 May 1995. Subsequently, I discovered a small population at Horseshoe Swamp, although I did not confirm breeding there. Several patrolling males were observed near the swamp-marsh edge on 13 June 1997. This is a record late date for this species in Virginia, exceeding the flight period (8 April - 25 May) given by Carle (1982). I suspect that *G. furcillata* also breeds in pond 18, a swampy, *Sphagnum*-covered pond, but I only visited this site once during mid-summer (i.e., after the adult flight season) and did not sample extensively for larvae on that date. Most previous records of this species in Virginia are from swampy habitats in the Coastal Plain (Carle, 1982; Roble et al., 1997; Roble & Cuyler, in press).

Gomphidae

+*Gomphus exilis* (Lancet Clubtail)

This is the only clubtail that I documented in the study area. My observations indicate that it is uncommon at the Maple Flats ponds, but I suspect it breeds at several ponds in this complex.

Corduliidae

**Cordulia shurtleffi* (American Emerald)

A small population of this northern species inhabits the Maple Flats area, where it is near its southern range limit in eastern North America (see Fig. 5 for Virginia distribution). Breeding was confirmed at Oak Pond, where two teneral males (one recently emerged from its exuvia; see Fig. 6) were found on 29 April 1997. The previous early flight date for Virginia was 25 May (Roble et al., 1997). My April record also appears to establish a new early emergence date for this species, exceeding the rangewide flight period (2 May - 26 August) given by Needham & Westfall (1955), Walker & Corbet (1975), and Carle (1982). At least half a dozen males were also observed patrolling (feeding ?) in the acidic seepage swamp portion of Horseshoe Swamp on 13 June 1997. A larger population of *C. shurtleffi* inhabits the Loves Run Pond. Territorial males patrol just above the surface of this heavily vegetated pond and are difficult to observe and count. I estimated that at least 25 males were present during my survey of 20 June 1995, but noted only one and 2-3 males during subsequent, but less thorough surveys on 10 June 1996 and 18 June 1998, respectively. Carle (1982) did not record this species at Quarles Pond and I did not observe it at Green Pond.

**Epitheca cynosura* (Common Baskettail)

This species is very common in the Maple Flats area in early spring. I observed numerous adults just prior to dusk on several occasions along Forest Service Road 42 (Coal Road) near South Pond. Two dead adults were found in spider webs.

+*Somatochlora tenebrosa* (Clamp-tipped Emerald)

Although breeding was not confirmed, I regularly encountered a few adults (maximum of 8/d; mostly females) of this species during my visits to the Maple Flats pond complex in late summer. They were observed at several ponds and along nearby forest trails. It is likely that a small resident population inhabits this area.

Macromiidae

Didymops transversa (Stream Cruiser)

One adult was observed while perched on a sapling branch along a forest trail near North Pond on 29 April 1997. This species probably breeds in Canada Run (possible sighting on 13 June 1997) and other streams in the Big Levels area.

Libellulidae

**Celithemis elisa* (Calico Pennant)

This species is common in the Maple Flats area and at Green Pond. I also found several adults in a gas pipeline right-of-way near Loves Run Pond, but saw only two males at the pond itself (different dates). My record for 26 September exceeds the previously reported (Roble & Hobson, 1996) late date for this species in Virginia by 13 days.

**Celithemis fasciata* (Banded Pennant)

A single male was observed at South Pond on 13 July 1995. Two weeks later I recorded this species at three ponds in the Maple Flats complex, including a mating pair and an ovipositing female at North Pond. These are my only records for this species in the study area.

**Celithemis martha* (Martha's Pennant)

My discovery of a small population of this species at Spring Pond was unexpected. I recorded eight adults (6♂, 2♀), including at least three tenerals, on 27 July 1995. Only two males were observed during a 0.5 h survey of the east end of this pond on 30 August 1996.

Martha's pennant (Fig. 7) is a Coastal Plain species which ranges from Nova Scotia to northern Virginia (Fig. 8). The Maple Flats population is both the most inland and the southwesternmost known locality for this species. Previous reports of *C. martha* from Ohio (Walker & Corbet, 1975) and the Carolinas (Huggins & Brigham, 1982) are not supported by voucher specimens and are believed to be erroneous (Glotzhober, 1995; Roble & Hobson, 1996).

**Celithemis verna* (Double-ringed Pennant)

This species was documented at four ponds in the Maple Flats area; it was most common at Spring Pond and the buttonbush pond at Horseshoe Swamp (ca. 40 males on 13 June 1997 at latter site). I found two adults of each sex, including one live male, ensnared in spider webs. Available records indicate that *C. verna* is rare in Virginia (Fig. 5). Although it is typically regarded as an early summer species, my records for *C. verna* extend as late as 18 August, exceeding Carle's (1982) latest record for Virginia by two months. Orr (1996) also recorded *C. verna* on 18 August in Maryland. Both of our records establish a new rangewide late flight date for this species, which was previously recorded as 26 July (Needham & Westfall, 1955; Carle, 1982).

**Erythemis simplicicollis* (Eastern Pondhawk)

This species is fairly common in the Big Levels area, but not as abundant as it is in many other lentic habitats throughout Virginia.

**Erythrodiplax minuscula* (Little Blue Dragonlet)

During the first several years of my surveys, I obtained only two records of this diminutive dragonfly from the Maple Flats area; both (1♂, 1♀) were found along a forest trail beside South Pond. On 30 August 1996, I observed a total of five adults (1 mature ♂, 4 teneral ♀) at Spring Pond and the Horseshoe Swamp marsh, thus confirming breeding in the Maple Flats area.

Leucorrhinia frigida (Frosted Whiteface)

Needham & Westfall (1955) reported this boreal species from Virginia for the first time but did not provide detailed locality information. Carle (1982) listed a specimen that he obtained in Highland County on 18 June 1978, and a potentially dubious larval record from Louisa County (Voshell & Simmons, 1976), but he did not include any historical records. The source of the original Virginia record was a specimen in the collection of Cornell University (M. J. Westfall, Jr., pers. comm.). Handwritten label data associated with this specimen (uncertain text is noted in brackets) are: "Green Pond, N.d. [?]{U. of Richmond, Va.}VI 14 1938/Tray [Troy?] Coll." (J. K. Liebherr, pers. comm.). Although the exact origin of this specimen may never be known, a review of Biggs (1974) reveals that the only "Green Pond" labeled on U.S. Geological Survey topographic maps of Virginia is in Augusta County. Specifically, it is the site treated as Green Pond in the present paper. However, as noted previously, Quarles Pond was referred to as Green Pond in the past by several botanists (e.g., Carr, 1938, 1940). Regardless of whether or not the Cornell specimen of *L. frigida* was collected at one of these two ponds, it appears that there is no resident population of this species at either site. Carle (1982) did not list this species for Quarles Pond and I did not observe it at Green Pond. This species is not included in the various summary tables in this paper.

**Leucorrhinia intacta* (Dot-tailed Whiteface)

Carle (1982) recorded this northern species at Quarles Pond on 13 June 1980. I captured one of two adult males observed at North Pond on 24 June 1992. A small population was subsequently (9 June 1995) discovered at Horseshoe Swamp by DNH botanist J. Christopher Ludwig. I observed this species there on several occasions (maximum of 40-50 males on 13 June 1997), and also recorded it at Oak and Spring ponds. Small populations of *L. intacta* also inhabit Loves Run Pond and Green Pond; my peak counts for both sites were ca. 25-30 males (plus a few pairs). Carle (1982) reported that the flight period of Virginia populations of this species extends from 17 May to 10 July; my records in the study area ranged from 29 April to 25 July.

I observed males of *L. intacta* chasing males of *Celithemis verna* on several occasions at the Horseshoe Swamp buttonbush pond on 13 June 1997. These species are similar in size, which may account for this interspecific agonistic behavior. The Maple Flats area is the only site in Virginia where these species (both are rare in the state) are known to occur syntopically (Fig. 5); *L. intacta* is primarily a northern species and *C. verna* is basically a southern species. The range of *L. intacta* extends south to Kentucky and Tennessee, but there are no records for North Carolina (Trogdon, 1961; Resener, 1970; Huggins & Brigham, 1982; Bick, 1997; R. D. Cuyler, pers. comm.).

**Libellula auripennis* (Golden-winged Skimmer)

I recorded a minimum of 20 males of this species at Loves Run Pond, plus 3-5 more at the nearby marshy pond, on 20 June 1995. At least 10 adult males and three mated pairs were observed at Horseshoe Swamp later that same day (but none was present on 13 June 1997). Otherwise, I noted this species only infrequently in the Maple Flats pond complex (e.g., several adults at South

Pond on 18 August 1993). These are the first Virginia records from outside of the Coastal Plain (Fig. 5). Carle (1982) did not list *L. auripennis* for Quarles Pond. My observation of 30 August exceeds the previous Virginia late date of 18 August that was reported by Roble & Hobson (1996).

+*Libellula axilena* (Bar-winged Skimmer)

I observed at least 20 males of this species at Loves Run Pond (n = 5) and the nearby marshy pond (n = 15+) on 20 June 1995. No less than 10 adults were also present at the Horseshoe Swamp marsh on this same date; I saw a maximum of five adults during a subsequent visit on 13 July (one of these was a dying male with very tattered wings), but only one male and one female were recorded on 13 June 1997. At least 10 males were present at Oak Pond on 27 July 1995.

**Libellula cyanea* (Spangled Skimmer)

This species was fairly common in the Maple Flats pond complex (recorded at 5 ponds); it was also present at all of the other study areas.

**Libellula deplanata* (Blue Corporal)

This is a spring and early summer species that was recorded infrequently in the Maple Flats area. I found one live male captured in a spider web on 31 May. My latest record (8 July) exceeds Carle's (1982) latest date for Virginia populations (12 June) by nearly a month.

**Libellula incesta* (Slaty Skimmer)

This species was common and widespread in the Maple Flats pond complex (documented at all study sites except pond 18). It was also recorded at Loves Run Pond and Quarles Pond, but not observed by me at Green Pond.

Libellula luctuosa (Widow Skimmer)

The widow skimmer was surprisingly rare in the study area and apparently not a local breeder. I observed lone males at or near South Pond on 18 August 1993 and 27 July 1995. Lone males were also seen in a gas pipeline right-of-way near Loves Run Pond on 20 June and 27 July 1995.

**Libellula lydia* (Common Whitetail)

This species was common and widespread in the Maple Flats pond complex (documented at eight study ponds). It was also common at Green Pond.

Libellula pulchella (Twelve-spotted Skimmer)

My records for this species in the Maple Flats pond complex are limited to seven individuals (5♂, 2♀) that were observed on six different dates ranging from 10 June to 20 September; Kurt Buhlmann collected a male at one of these ponds on 3 June 1990. I also observed a lone male at Loves Run Pond on 30 August 1996. Carle (1982) reported that the flight period extends from 29 April to 19 September in Virginia. This species may breed in the study area.

**Libellula semifasciata* (Painted Skimmer)

This species was common in the study area, being most abundant at the Horseshoe Swamp marsh. It was the most abundant skimmer in this sedge marsh on 13 June 1997, when at least 50 adults were present.

**Pachydiplax longipennis* (Blue Dasher)

The blue dasher was common at Loves Run Pond and common to abundant at various ponds in the Maple Flats complex (recorded at 9 of 11 study ponds). It was the dominant species in terms of abundance during one of my few visits to Split Level Pond.

**Sympetrum rubicundulum* (Ruby Meadowhawk)

This late summer and fall species was common in the Maple Flats area, being most conspicuous at South, North, and Twin ponds. It was also common at Loves Run Pond. I did not record it at Green Pond (all of my surveys were in early-mid summer), but Michael S. Hayslett collected a female there on 22 August 1996 (specimen currently in DNH collection).

**Sympetrum semicinctum* (Band-winged Meadowhawk)

Carle (1982) collected a mated pair of this species at Quarles Pond on 29 October 1978. I did not observe it at any of my study ponds, but have found it elsewhere in Augusta County at the Cowbane Prairie Natural Area Preserve along the South River southwest of Sherando.

**Sympetrum vicinum* (Yellow-legged Meadowhawk)

This late summer and fall species was common and widespread in the study area.

**Tramea carolina* (Carolina Saddlebags)

This reddish species is common in the Big Levels area. It was recorded at all study sites except pond 18.

**Tramea lacerata* (Black Saddlebags)

My few records for this species are limited to South, Twin, and Loves Run ponds. Except for two males that I noted at Twin Pond on 30 August 1996, all of my records consist of one adult per visit. However, these observations include an ovipositing female at Loves Run Pond on 18 June 1998, suggesting that this species breeds in the study area.

Table 7. Comparison of the Odonata fauna of the Shenandoah Valley sinkhole pond system and vicinity, Augusta County, Virginia, with selected other areas in Virginia and the eastern United States.

Reference	State	Locality/Habitat	Pond breeders	Shared species[a]	Overlap as % of Big Levels fauna	Percent similarity[b]
Roble & Hobson 1996	VA	Fort A. P. Hill Military Reservation, Caroline County (Coastal Plain ponds)	59	41	75.9	56.9
Roble & Stevenson 1998	VA	Grafton Ponds, York County (sinkhole pond complex)	36	27	50.0	42.9
Roble & Cuyler in press	VA/NC	Great Dismal Swamp and vicinity (various lentic habitats)	58	34	63.0	43.6
Carle 1982; Flint, unpubl. data; Roble, unpubl. data	VA	Laurel Fork Recreation Area, George Washington Nat. For., Highland Co. (montane beaver pond complex)	50	33	61.1	46.5
Donnelly 1961	VA/MD	Washington, D.C. area (various lentic habitats)	68	44	81.5	56.4
Orr 1996 + pers. comm. additions	MD	Patuxent Wildlife Research Center (various lentic habitats)	76	49	90.7	60.5
Ahrens 1968; Orr 1998	MD/WV	Cranesville Swamp (montane bog and beaver ponds)	50	34	63.0	48.6
Harwood 1974	WV	Pendleton County (various lentic habitats)	28	22	40.7	36.7
Harwood 1979	WV	Pocahontas County (various lentic habitats)	32	21	38.9	32.3
Shiffer & White 1995	PA	Ten Acre Pond, Centre County	71	42	77.8	50.6
White et al. 1968	PA	Bear Meadows Bog, Centre County	47	28	51.9	38.4
White 1989	ME	Acadia National Park and vicinity (various lentic habitats)	87	36	66.7	34.3
Gibbs & Gibbs 1954; Carpenter 1991; Nikula 1996	MA	Cape Cod, Barnstable County (Coastal Plain ponds)	84	48	88.9	53.3
Van Buskirk 1992	MI	Isle Royale National Park	43	10	18.5	11.5
Cross 1955; Kondratieff & Pyott 1987	SC	Savannah River Plant (various lentic habitats)	41[c]	23[c]	65.7	43.4

[a] Species in common with the fauna of the Shenandoah Valley sinkhole pond (SVSP) system and vicinity; based on 54 species of pond-breeding Odonata documented at the Maple Flats pond complex, Loves Run Pond, Quarles Pond, and Green Pond, including 35 species of Anisoptera (dragonflies).

[b] Percent similarity = Number of Shared Species / (Total Species from SVSP system and vicinity + Total Species at comparison site - Number of Shared Species)

[c] Only includes Anisoptera.

Tramea onusta (Red-mantled Saddlebags)

An adult male that was collected at Green Pond on 2 July 1991 by C. A. Pague constituted only the third documented record of *T. onusta* in Virginia (Roble et al., 1997). I did not observe this species during three early-mid summer visits to this site and doubt if it breeds in the Big Levels area. *Tramea onusta* is primarily a southern species that wanders widely in late summer. I regard it as a vagrant or accidental species in Virginia.

DISCUSSION

The dragonfly and damselfly fauna of the Shenandoah Valley sinkhole pond system is rather diverse, accounting for nearly one-third of Virginia's known Odonata fauna (Table 5). Excluding the families Calopterygidae, Gomphidae, Cordulegastridae, and Macromiidae, the members of which breed primarily or exclusively in running water, this percentage becomes even greater (45%). I regard this community of dragonflies and damselflies as one of the most diverse and interesting assemblages of lentic species known in the state. It contains a considerable number of species that are monitored as rare or uncommon taxa (Roble, 1996) by the Virginia Department of Conservation and Recreation's Division of Natural Heritage (Table 6). The proportion (= 15%) of state-rare species of Odonata that inhabit the Shenandoah Valley sinkhole pond system is virtually identical to that documented for the Fort A. P. Hill Military Reservation in Caroline County, which Roble & Hobson (1996) also regarded as a significant lentic Odonata fauna. The vascular flora of sinkhole ponds and seepage wetlands in the study area contains a comparable proportion of state-rare species (34 of 274 species, or 12%) (Fleming & Van Alstine, 1999), whereas only one state-rare amphibian has been documented at sinkhole ponds in this region (Mitchell & Buhlmann, 1999).

The composition of the Odonata fauna of the Shenandoah Valley sinkhole pond system is compared with other sites in Virginia and the eastern United States in Table 7. The Shenandoah Valley fauna is considerably more diverse than the recently documented (Roble & Stevenson, 1998) fauna of the Grafton Ponds sinkhole complex (York County) on Virginia's Lower Peninsula and is comparable in diversity to the Coastal Plain pond fauna of Fort A. P. Hill (Caroline County) and the montane beaver pond fauna of the Laurel Fork Recreation Area (Highland County). Although the latter site is nearer to the Shenandoah Valley study area, Fort A. P. Hill shares a considerably greater (76% vs. 61%) proportion of the fauna. The areas exhibiting the greatest species overlap with the Shenandoah Valley sinkhole pond system are the Patuxent Wildlife Research Center in eastern Maryland and Cape Cod, Massachusetts (Table 7). During a nine-year survey of the former site, Orr (1996; pers. comm.) documented 54 of the 60 species present in the Shenandoah Valley study area, including 20 of 21 damselflies. Only the following species were not recorded at his study site: *Enallagma doubledayi, Aeshna constricta, A. tuberculifera, Boyeria grafiana, Cordulia shurtleffi,* and *Leucorrhinia intacta*. The fauna of Cape Cod includes 52 of the 60 species documented in the Shenandoah Valley study area.

The geographic affinities of the Odonata fauna of the Shenandoah Valley sinkhole pond system are summarized in Table 8. As expected, my analysis reveals a preponderance (67%) of species that are widespread in eastern North America or the entire continent. Most of the remaining species are evenly divided between those with predominantly northern or southern distributions. As noted previously in the species accounts, the discovery of apparently isolated populations of *Celithemis martha* and *Nehalennia integricollis*, both of which have predominantly Coastal Plain distributions, was unexpected. Curiously, the former species is at the extreme southwestern limit of its range at Maple Flats, whereas the latter species is known primarily from the southeastern United States (compare Figs. 4 and 8).

Table 8. Geographic affinities of the Odonata fauna of the Shenandoah Valley sinkhole pond system and vicinity.

Distribution	Maple Flats ponds: All species	Maple Flats ponds: Breeders	Shen. Valley study ponds	Percent
Continental	9	9	9	15.0
Eastern	28	23	31	51.7
Northern	7	7	8	13.3
Southern	7	6	8	13.3
Midwestern	1	1	1	1.7
Appalachian	1	0	1	1.7
Coastal Plain	2	2	2	3.3
Endemic	0	0	0	0
Total	55	48	60	100

Fleming & Van Alstine (1999) performed a similar geographic analysis for the vascular flora that has been documented at sinkhole ponds and seepage wetlands in the Big Levels - Maple Flats area. They determined that the majority of these species were widely distributed, which agrees with the results for Odonata. Plant species with more restricted ranges were dominated by northern species, followed by southeastern taxa and Coastal Plain species. The latter group accounted for 7.3% of all plants in the Big Levels - Maple Flats wetlands and 10.9% of those at sinkhole ponds (Fleming & Van Alstine, 1999).

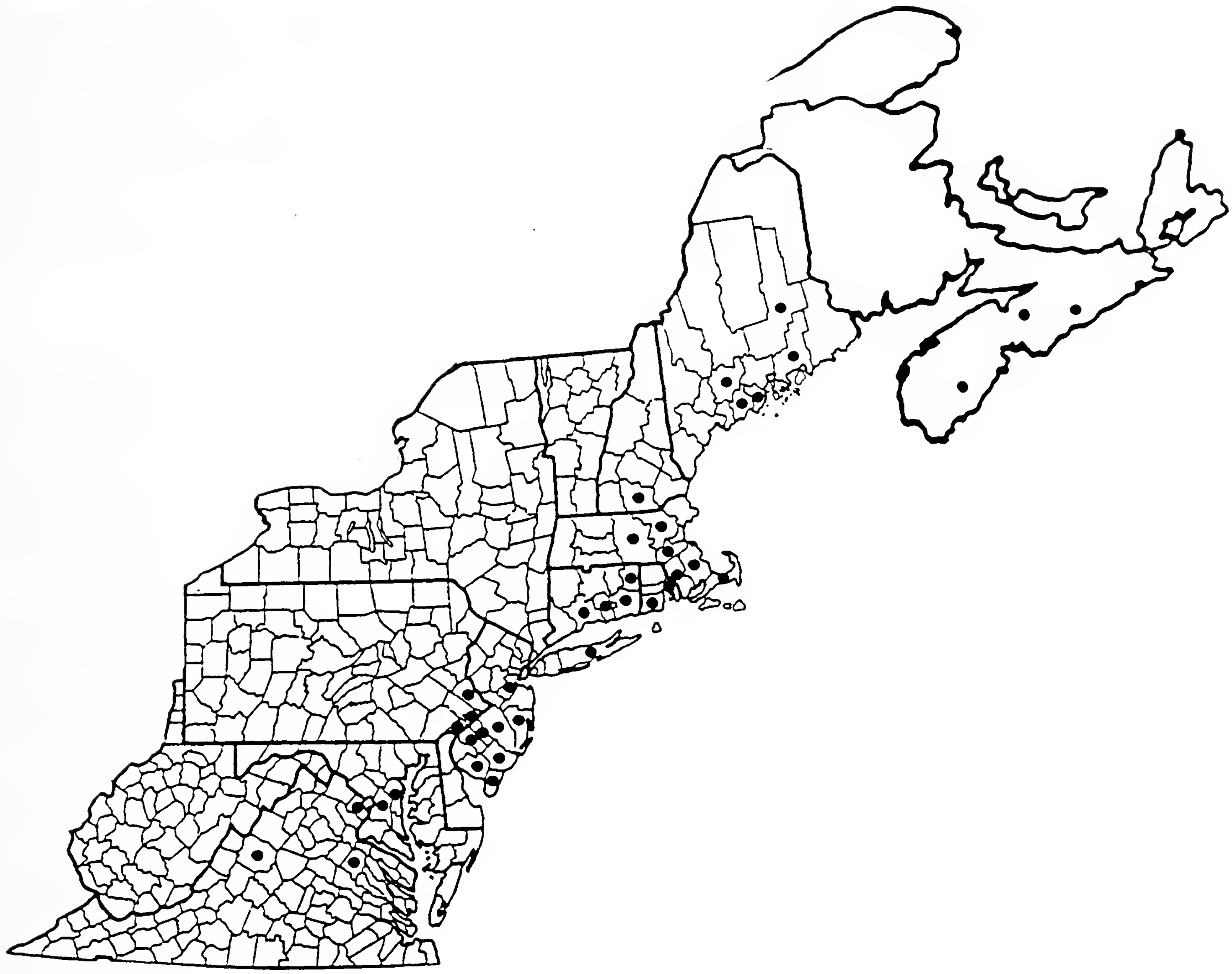

Fig. 8. Geographic distribution (by county) of Martha's pennant (*Celithemis martha*). See Appendix for data sources.

By comparison, only two of the 55 species (3.6%; increases to 4.2% if non-breeders are excluded) of Odonata that I recorded at the Maple Flats ponds have primarily Coastal Plain distributions. The Maple Flats flora also includes one species that is endemic to the Shenandoah Valley (and another that is endemic to Virginia), whereas there are no endemic species of Odonata in Virginia.

Craig (1969) conducted a palynological study of Spring Pond (reported as Hack Pond) and concluded that an oak-hickory forest replaced the preceding spruce-dominated (boreal) forest about 10,000 B.P. during glacial retreat. Harvill (1992) postulated that elements of the Coastal Plain flora that occur in the Shenandoah Valley migrated inland after the decline of the boreal forest but while the climate of the region was still oceanic. He further believed that as the climate of the region became more continental, most populations of these (moisture-sensitive) plant species were extirpated, leaving only a few relict populations in particularly suitable habitats.

Shapiro (1971) reported that a number of butterfly species exhibit disjunctions in their ranges between Atlantic Coastal Plain and Great Lakes populations, a well-known phenomenon in plants. To my knowledge, none of the butterfly species with strong breaks in their ranges (e.g., black dash, *Euphyes conspicuus*) has been recorded in the Shenandoah Valley of Virginia. Prior to my study, the tiger salamander (*Ambystoma tigrinum*) was the only animal that was confirmed to occur in the Shenandoah Valley sinkhole pond system as a disjunct population from the Coastal Plain region of Virginia (Buhlmann & Hoffman, 1990).

If Harvill's (1992) dispersal hypothesis is correct, perhaps *Celithemis martha* and *Nehalennia integricollis* reached the Maple Flats sinkhole pond complex by a similar route and now represent relict populations. The only site where the former species was documented during this study is Spring Pond, which is the most unique habitat in the Maple Flats area (Rawlinson & Carr, 1937; Fleming & Van Alstine, 1999). Fleming & Van Alstine (1999) stated that the dominant plant community of Spring Pond may represent a Coastal Plain disjunct. The most comparable wetland known to me in Virginia is a large, boggy, golden club-dominated pond on the Fort A. P. Hill Military Reservation, where *C. martha* also occurs (site 29 in Roble & Hobson, 1996). This species was documented at five other boggy ponds on that military base as well as one small, boggy pond located elsewhere in the county; *N. integricollis* was recorded at five sites on the base. These sites are approximately 150 km east of the Maple Flats ponds, but represent the nearest confirmed populations of both species to date (Roble, 1994; Roble & Hobson, 1996).

More intensive sampling of the Odonata fauna of the Shenandoah Valley sinkhole pond system may reveal the presence of additional species that were not documented during this study. Notable absences include the unicorn clubtail (*Arigomphus villosipes*), wandering glider (*Pantala flavescens*), and eastern amberwing (*Perithemis tenera*). Additional surveys of Quarles and Spring ponds are particularly warranted, as is sampling of other ponds in the Maple Flats (e.g., Deep Pond) and Loves Run pond complexes that were not included in the present study. Nearby ponds outside of the forest service boundary, such as Hattons Pond and the five ponds in the Sherando Pond complex (sensu Buhlmann et al., 1999), have not been surveyed for Odonata. Apparently, no historical collections of Odonata (or other aquatic insects) are available from a site known as Mountain Lake, Shenandoah Acres, the largest sinkhole pond in the Big Levels region. This was a botanically significant site (Carr, 1938, 1940), but it was destroyed sometime during the past half century and currently functions as a recreational swimming pond for a private campground. The only invertebrate records known to me from this site are of two state-rare skippers, one of which was mentioned in Clark & Clark (1951). These authors listed a 5 July 1937 record of the two-spotted skipper (*Euphyes bimacula*), which constituted the first Virginia record of this species (female specimen in USNM). A specimen of the mottled duskywing (*Erynnis martialis*) that was collected near this sinkhole pond on the same date is also in the USNM.

There is an urgent need to survey many other sinkhole ponds in the Shenandoah Valley of Augusta, Rockingham, and southern Page counties for rare and unusual aquatic insects, as well as amphibians. Many of these ponds, most of which are privately owned, have been visited by botanists (e.g., Longbottom & Van Alstine, 1995; Van Alstine, 1996), but very few have been surveyed by zoologists. It will be interesting to learn if other groups of aquatic insects (e.g., Coleoptera, Heteroptera) are represented in the Shenandoah Valley by Coastal Plain disjuncts, boreal relicts, or rare species.

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APPENDIX

Data sources (by state) consulted to prepare the county distribution maps of *Nehalennia integricollis* (Fig. 4) and *Celithemis martha* (Fig. 8). Museum abbreviations are: FSCA/IORI = Florida State Collection of Arthropods and International Odonata Research Institute, Gainesville, Florida; MCZ = Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts; USNM = National Museum of Natural History, Smithsonian Institution, Washington, D.C.; YPM = Peabody Museum of Natural History, Yale University, New Haven, Connecticut.

Alabama: Tennessen et al. (1995)
Connecticut: Wagner & Thomas (in press); D. L. Wagner, pers. comm.
Delaware: no records (H. B. White, pers. comm.)
Florida: Dunkle (1992)
Georgia: Calvert (1913); Root (1924); Williamson (1934); FSCA/IORI; S. W. Dunkle, pers. comm. (unpublished data); W. F. Mauffray, pers. comm. (unpublished data)
Louisiana: Mauffray (1997)
Maine: Borror (1944, 1951); White (1989); Williamson (1922); P.-M. Brunelle, pers. comm.
Maryland: Donnelly (1961); Fisher (1940); Orr (1996); Williamson (1922); USNM; R. L. Orr, pers. comm.
Massachusetts: Carpenter (1991); Howe (1920; reported as *Celithemis ornata*); White (1979); Williamson (1922); MCZ; USNM; YPM
Mississippi: Lago et al. (1979); FSCA/IORI; S. W. Dunkle, pers. comm. (unpublished data); W. F. Mauffray, pers. comm. (unpublished data)
New Hampshire: White & Morse (1973); P.-M. Brunelle, pers. comm.
New Jersey: May & Carle (1996)
New York: Donnelly (1992)
North Carolina: R. D. Cuyler, pers. comm. (unpublished data); FSCA/IORI
Nova Scotia: Brunelle (1997); Cook (1950); Walker & Corbet (1975); P.-M. Brunelle, pers. comm. (unpublished data)
Oklahoma: Bick & Bick (1957); USNM
Pennsylvania: Beatty & Beatty (1971); C. N. Shiffer, pers. comm.
Rhode Island: Carpenter (1998); Nikula (1998); V. A. Carpenter, pers. comm.(unpublished data)
South Carolina: White et al. (1983)
Texas: Johnson (1972)
Virginia: Carle (1982); Gloyd (1951); Matta (1978); Roble (1994); Roble & Hobson (1996)
State distributions (general): Bick (1997); Needham & Westfall (1955); Westfall & May (1996)

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Amphibians and Reptiles of the Shenandoah Valley Sinkhole Pond System in Virginia

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INTRODUCTION

Seasonal ponds are used extensively for breeding and larval development and as foraging habitat by amphibians and reptiles. Complexes of ponds or freshwater wetlands free of fish are critical habitats for some species in eastern North America. Ephemeral or vernal pools, such as those created by sinkhole pond formation, offer a dynamic habitat for these animals because of variation in hydrological regimes and timing of water gain or loss. However, levels of herpetofaunal diversity and population dynamics in local regions are tied directly to the dynamics of these habitats. Landscape features such as temporary breeding ponds have been called keystone habitats because they can determine species presence or absence (Primack, 1998).

Natural sinkhole ponds in the Shenandoah Valley in the Big Levels area of Augusta County, Virginia, provide a dynamic mosaic of wetland habitats used by a diversity of amphibians for breeding. They may in fact be keystone habitats in this region. Some reptiles use these ponds temporarily. The ponds exhibit a wide range of variation in size, depth, and vegetation characteristics, occur over a relatively narrow range of elevations, and dry at different times of the year (Buhlmann et al., 1999). Some of them seldom dry at all or only during prolonged drought. Others dry frequently. Species of frogs and salamanders that use these habitats must be able to withstand the many uncertainties of breeding in ephemeral pools. Individuals of these species are long lived and are able to tolerate some years of complete reproductive failure. Others are explosive breeders and their population numbers fluctuate dramatically. And still others move between wetlands as the ponds dry. Some species use the ponds annually or over a period of several years, whereas others occur there for only brief periods of time.

The Shenandoah Valley Sinkhole Ponds (SVSP) system in the Big Levels region of the George Washington National Forest offers a dynamic landscape that supports a unique assemblage of amphibians and reptiles. The composition of the fauna is tied directly to the unique habitats provided by sinkhole ponds. Some of these populations have apparently been here since at least the Pleistocene Epoch (Guilday, 1962). These ancient lineages and the presence of boreal and coastal plain disjunct populations of diverse floral and faunal species (Rawlinson & Carr, 1931; Carr, 1937; Fleming & Van Alstine, 1999; Roble, 1999) make the Shenandoah Valley sinkhole ponds area a biologically unique environment.

We have been studying amphibians and reptiles of this area since 1986 and have accumulated numerous observations on many species. Our objectives in this paper are to

summarize our natural history observations on the local herpetofauna and to discuss conservation and management issues pertinent to these animals.

MATERIALS AND METHODS

Descriptions and locations of the ponds in the SVSP system are found in Buhlmann et al. (1999). One of us (JCM) first visited the SVSP system on 18 July 1986 during which several natural history observations were made and specimens collected; these were donated to the National Museum of Natural History. KAB began a systematic inventory in late 1987 and, with the exception of 1991 and 1993, both of us accumulated information on all of the amphibians and reptiles in most months of the year (January-October) through 1998. On 3 and 8 March 1988, we installed four isolated drift fences with pitfall traps following designs in Gibbons and Semlitsch (1982) adjacent to Ponds 2, 16, and 17, and between Ponds 12 and 13. We used single lengths of 7.5 x 0.6 m aluminum flashing erected upright and buried in the ground about 10 cm. We buried a 19 l (5 gallon) plastic bucket flush to the ground at each end of each fence. We placed water and leaves in each pitfall to reduce animal mortality and provide cover. Drift fence/pitfall arrays were in operation 1988 and 1989 from January until April during which we checked the arrays every 1-2 days.

During each field trip to the SVSP system, we systematically surveyed several ponds visually and searched for larval and adult amphibians, often using aquatic dip nets to capture individuals. We measured many of the animals caught (straight-line snout-vent length [SVL] for frogs, salamanders, and snakes; carapace [CL] and plastron length [PL] for turtles) to the nearest mm and weighed many individuals with Pesola® scales to the nearest gram. We also took notes on phenotypic variation, abnormalities, injuries, and parasites. We marked turtles by filing notches in the margin of the carapace using the 1-2-4-7 system described in Mitchell (1988). Tadpole developmental stages follow the classification of Gosner (1960).

RESULTS

We obtained information on 20 species of amphibians (11 frogs and toads, 9 salamanders) and 10 species of reptiles (4 turtles, 6 snakes). One of the salamander species is listed as endangered by the Virginia Department of Game and Inland Fisheries and one turtle is considered to be sensitive to habitat alteration and commercial harvest (Ernst et al., 1994).

Annotated species list

In the following species accounts, we summarize observations and data accumulated over a 12-year period on aspects of seasonal occurrence, ponds inhabited, breeding dates, number of egg masses, larval presence and growth, dates of metamorphosis, body size, and sexual dimorphism. We also note effects of pond drying on selected species. Pond names and numbers follow Buhlmann et al. (1999). Common and scientific names follow Crother (in press).

Frogs

1. *Acris crepitans crepitans* (Northern Cricket Frog) (Ponds 2, 10, 13, 16, 17, 20, 23, 24, 33, Maple Flats North and South, Spring Pond)

This small frog was abundant in many of the sinkhole ponds in the SVSP system. The first specimens collected from this area were on 4, 11, and 18 July 1986 (USNM 347846-57, 347878-82). Dates of earliest and latest observations of active individuals were 2 February and 27 September, respectively. We recorded calling males between 18 May and 13 July. We observed adults in amplexus on 28 June and metamorphs on 18 July, 1, 8, & 14 August, and 12 & 21 September. The smallest female with yolked follicles was 20.6 mm SVL. One tadpole was observed being eaten by a giant water bug (*Lethocerus americanus*) on 1 August 1996. Of 40 frogs caught on 23 June 1997 at Pond 13, dorsal stripe color varied from red (2.5%) to green (35%) to brown (62.5%). Females (23.4±0.7 mm SVL, range = 22-25, n = 12; 1.3±0.2 g body mass, 1.1-1.4, n = 6) averaged slightly larger than males (21.0±1.4 mm SVL, 19-24, n = 43; 0.8±0.1 g, 0.7-0.9, n = 3). Only one abnormal individual was caught, a female with a missing left rear foot found at Quarles Pond on 27 April 1988.

2. *Bufo americanus americanus* (Eastern American Toad) (Ponds 2, 11, 12, 13, 14, 16)

We recorded breeding American toads from five ponds. Dates of observation of adults were between 2 March and 8 May. Males were heard calling between 14 April and 8 May. We found a gravid female on 30 March 1988. We noted tadpoles in Pond 14 on 23 March 1995. Three males measured 63, 68, and 78 mm SVL; the latter two weighed 35 and 45 g, respectively.

3. *Bufo fowleri* (Fowler's Toad) (Pond 2)

Fowler's toads apparently seldom use the sinkhole ponds for breeding. Only in Pond 2 did we find tadpoles and this was in shallow water that had been added to the pond by rain after it had dried completely a month before. Two

adults were collected on 18 July 1986 on the trail near Pond 11 (USNM 347862-63). Others were observed on trails and in a shallow pool at the eastern end of the Coal Road. Dates of observation were between 17 May and 28 June. The largest male of the small sample, found on the trail near Oak Pond, was 60 mm SVL and weighed 20.5 g; the largest female was 70 mm SVL and 37.5 g.

4. *Hyla versicolor* (Gray Treefrog) (Ponds 2, 11, 12, 13, 16, 17)

Gray treefrogs appear to be limited to a small number of ponds in the area. We heard males calling between 17 May and 21 September. Only one adult was observed outside this period, on 21 April 1989. We observed tadpoles between 6 July and 2 August. We found one recent metamorph on 17 September. Eight males measured 43-49 mm SVL (mean = 45.4±2.1).

5. *Pseudacris crucifer crucifer* (Northern Spring Peeper) (Ponds 2, 3, 4, 8, 10, 11, 12, 13, 16, 17, 21, 23, 25, 27, 29, Kennedy Mountain Meadow, Maple Flats North and South, Spring Pond)

This was a common anuran in the SVSP system. Six specimens were collected along the main trail between the gate and Pond 12 on 18 July 1986 (USNM 347864-69). Dates of calling were 2 February to 6 July and 17 September to 15 October. We observed amplexus on 29 April, 10 May, and 12 June. Tadpoles collected in June and July were in widely different stages of development, indicating multiple dates of egg deposition and variation in rates of larval development. A sample of 30 tadpoles caught on 17 May 1988 in Kennedy Mountain Meadow were in Gosner (1960) developmental stages 29-38 (limb bud to nearly full hind limb development). A sample of 14 tadpoles caught on 21 June 1988 in Pond 2 were in stages 29-44 (limb bud to nearly complete metamorphosis). We observed other metamorphs on 28 June and 6 July. Male vocalizations in fall months were not associated with breeding.

6. *Pseudacris feriarum feriarum* (Upland Chorus Frog) (Pond 10)

We heard one individual calling in Pond 10 on 25 March 1988 when it contained shallow water. Several localities are known for this species in adjacent Rockingham County but this is the only observation for Augusta County (Mitchell & Reay, in press).

7. *Rana catesbeiana* (American Bullfrog) (Pond 2, 11, 12, 13, 16, 17, Maple Flats North and South, Spring Pond)

Bullfrogs breed only in ponds with nearly permanent hydroperiods because tadpoles may take as long as two years to reach metamorphosis. Juveniles and occasionally adults inhabit ponds with highly dynamic hydrologies for short periods of time but do not reproduce in them. The first specimens collected were adults, one each from Pond 11 and Spring pond (USNM 3347870-71). We heard males calling between 28 May and 13 July. Active individuals were observed between 20 January and 7 October. We observed tadpoles in each month we visited the ponds (January - October) and metamorphs on 6 July, 1 August, and 14 October. The largest tadpole we measured was 132 mm total length. Ten juveniles averaged 57.2±11.3 mm SVL (43-74). The only adult we measured was a 146 mm SVL male. We found dead adults twice, once in the bottom of Pond 16 on 20 January 1990, possibly the result of freezing, and one on the main trail near Maple Flats North on 19 September 1992 from unknown causes.

8. *Rana clamitans melanota* (Northern Green Frog) (Ponds 1, 2, 4, 11, 12, 13, 16, 17, 35, Maple Flats North and South, Spring Pond)

Green frogs reproduce in sinkhole ponds that contain water for most months of the year because tadpoles require about a year to complete development. Pond drying can cause massive mortality of tadpoles; many tadpoles were found dead in the bottom of Pond 11 on 17 October 1998. Numerous metamorphs were present at Pond 5 on 4 October 1987 but were all gone ten days later. The first specimen from the area was a tadpole collected from Maple Flats North on 18 July 1986. Calling dates were between 10 May and 8 August; this is presumably the breeding period. Dates of earliest and latest active individuals were 29 January and 27 September, respectively. We found tadpoles in multiple growth stages, representing multiple bouts of reproduction, on 13 January 1995 in Pond 11, and we collected a series of tadpoles from Pond 17 on 2 February 1990 that represented Gosner growth stages 25-36. We observed tadpoles in Gosner stages 34 (n = 1), 35 (1), and 38 (3) on 17-18 May 1988. The largest tadpole we measured was 88 mm total length. We found metamorphic individuals on 28 June and 6 July; one with a tail bud weighed 6.9 g. Juveniles were observed in all months May through October. Three juveniles averaged 36.9 mm SVL (33-40).

9. *Rana palustris* (Pickerel Frog) (Ponds 2, 11, 12, 13, 17, 32, Maple Flats North and South, Spring Pond)

Pickerel frogs are probably more abundant in the SVSP system than observation records indicate. Almost half of

our records were derived from the drift fence/pitfall arrays. One adult was collected at Spring Pond and three tadpoles were obtained from Maple Flats North on 11 July 1986 (USNM 347873, 347890-92). Males were heard calling from 8 April to 6 June. We found one egg mass on 6 March 1996. We observed recently metamorphosed juveniles on 14 August (26 mm SVL) and 19 September. Two adult males were 50 and 53 mm SVL and two adult females measured 62-66 mm SVL. Juveniles and adults undoubtedly disperse through the SVSP complex on a regular basis because they have been found in several ephemeral ponds.

10. *Rana sylvatica* (Wood Frog) (Ponds 2, 11, 12, 13, 16, 17, 18, 23, 27)

Wood frogs breed earlier than any other anuran in the SVSP system. Inclusive dates of calling males are 2 February and 6 March. We found a gravid female on 14 March 1988 and pairs in amplexus on 27 February and 8 March. We observed egg masses between 24 February and 21 April and predation by marbled salamanders (*Ambystoma opacum*) larvae on the former date. Egg masses accumulate heat during the day and are often warmer than the surrounding open water (Waldman & Ryan, 1983). Temperatures 2 cm deep in two egg masses taken on a sunny 24 March 1995 were 24.2° C and 26.8° C and those of the adjacent water were 16.0° C and 21.8° C, respectively, at Pond 27. However, we found egg masses frozen above the waterline on 3 March 1988 in Pond 2, indicating the risks associated with breeding in seasonally fluctuating ponds (Fig. 1). We found two tadpoles (Gosner stages 37 and 39) on 21 June 1988. Adult males (mean = 55.0±3.2 mm SVL, range = 49-61, n = 12; 14.5±1.9 g body mass, 13.7-17.0, n = 12) were smaller than adult females (mean = 63.5, 61-66, n = 2; 24.4 g, 21.5-27.3, n = 2; both females were gravid).

11. *Scaphiopus holbrookii* (Eastern Spadefoot)

Only one individual of this fossorial species has been observed in the SVSP system. We collected an adult female (45 mm SVL) on 12 June 1987 on the main trail between Ponds 3 and 13. S.M. Roble (personal communication) confirmed the identification of a juvenile captured and released on the trail near Twin Ponds during a heavy rain on 10 June 1996.

Salamanders

12. *Ambystoma maculatum* (Spotted Salamander) (Ponds 2, 4, 5, 8, 9, 10, 13, 18, Elusive Pond, Kennedy Mountain Meadow, Maple Flats North)

Spotted salamanders, like all species in the genus *Ambystoma*, are terrestrial as adults, but return to sinkhole ponds to breed. Spotted salamanders entered sinkhole ponds later than tiger salamanders (*Ambystoma tigrinum*) (see below), and the larvae were sympatric with them and *A. opacum* larvae in several ponds. We found three adults under leaf litter at the edge of Pond 2 on 3 March 1988. The earliest date we observed adults in the ponds was 2 February 1990. We observed fresh eggs in February and early March. One egg mass had not hatched when observed on 21 April 1989. We measured individuals undergoing metamorphosis during late June through September in years when ponds retained water. Adults may be abundant in some ponds but we have never found many larvae. This may be due to the abundance of earlier fall-breeding marbled salamander whose larvae are large enough to eat hatchling spotted salamander larvae. High dragonfly densities have been shown to induce changes in coloration in tadpole tails (Caldwell, 1982; McCollum & Leimberger, 1997). Two spotted salamander larvae captured on 2 June 1998 in Pond 13 had diffuse black tail tips, suggesting that *A. maculatum* may also exhibit predator-induced polyphenism. The number of spots on the dorsum of the body and head of adults varied from 8-31 (mean = 18.4±4.1, n = 78).

13. *Ambystoma opacum* (Marbled Salamander) (Ponds 2, 3, 4, 5, 6, 11, 12, 13, 14, 16, 17, 23, 27, 32, Spring Pond)

Like other ambystomatids, marbled salamanders use many of the SVSP ponds for breeding. Adults leave their terrestrial, underground retreats in mid-September to move to breeding ponds that are usually dry at this time. Males deposit spermatophores in moist areas where they are picked up by females for internal fertilization (Noble & Brady, 1933). We found spermatophore stalks on 17 September. Females lay eggs under debris and moist logs along the edges of the ponds and remain with them until fall and winter rains. Water levels rise at varying rates but ultimately inundate the eggs. This can be as late as January in some years when the ground surrounding the eggs appears frozen (e.g., winter of 1987-1988, KAB, personal observation). Females then leave the ponds and return to underground retreats. Emersion in water causes eggs to hatch in <1 wk to 2.5 months (Noble & Brady, 1933). We have observed larvae in ponds January through mid-June. These larvae grow from about 11 mm SVL at hatching to about 30-35 mm SVL at metamorphosis. They often cannibalize each other and are important predators of other ambystomatid larvae in several ponds. Known predators of marbled salamander larvae in some ponds are larger *A. tigrinum* larvae and northern watersnakes (*Nerodia sipedon*). Eggs of this species in this area are

Fig. 1. Wood frog eggs exposed by pond drying, illustrating the potential variation of reproductive success due to changing environmental conditions. (Photo by KAB.)

Fig. 2. The first *Ambystoma tigrinum* (a recent metamorph) known from the SVSP system, Augusta County, Virginia. (Photo by JCM.)

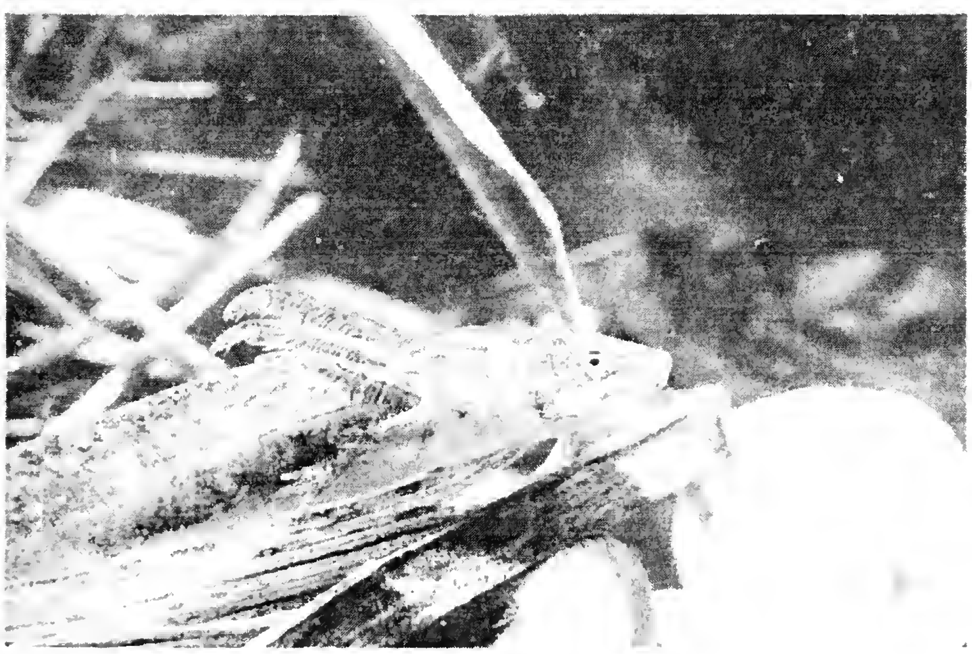


Fig. 3. *Ambystoma tigrinum* larva from the Shenandoah Valley sinkhole pond system, Augusta County, Virginia. (Photo by KAB.)

apparently eaten occasionally by carnivorous millipeds, *Uroblaniulus jerseyi* (Mitchell et al., 1996). We observed successful reproduction in most years in ponds used for breeding. However, when ponds dry before late-May, as in 1997, all or most of the larvae die before reaching metamorphosis. Of 31 individuals for which we have phenotype data, 10 had a complete set of dorsal crossbars, 18 had 1-2 broken crossbars, 2 had parallel stripes instead of crossbars, and 1 had a combination of parallel stripes and crossbars.

14. *Ambystoma tigrinum tigrinum* (Eastern Tiger Salamander)

Specific locations for this species are not provided because *A. tigrinum* is listed as Endangered in Virginia (Mitchell, 1991; Pague & Buhlmann, 1991). The first specimen known to us was a recent metamorph caught on 18 July 1986 by H.P. Whidden (Fig. 2). This salamander was not preserved and subsequently lost. Buhlmann & Hoffman (1990) reported the first voucher specimen (CM 118612) collected from a shallow sinkhole pond on 12 May 1987 in the SVSP system. Tiger salamanders use several of the sinkhole ponds for breeding. We have counted egg masses in up to six ponds in most years between 1988 and 1998. Adults enter the ponds in January and February, mate, lay eggs, and then return to their underground retreats in adjacent hardwood forests where they spend most of their adult lives. Eggs are predated upon by *Notophthalmus viridescens* and *Ambystoma opacum* larvae, as well as several species of invertebrates. Tiger salamander larvae (Fig. 3) remain in water until summer months. Metamorphosis can occur as early as mid-June if the pond dries during that time. Early pond drying can cause variation in size at metamorphosis, as metamorphs found around one dry pond on 28 June 1990 were smaller (51-54 mm SVL) than gilled larvae (55-65 mm SVL) in a nearby pond with water. If the pond dries earlier than June, larvae do not survive, as was the case in several ponds in the SVSP system in 1995 and 1997. Seasonal variation in pond hydrology, as illustrated in Fig. 4, can cause some ponds used by salamanders for reproduction to be unproductive in some years, while others in the area with water produce population recruits annually or nearly so. Tiger salamanders in the SVSP system should be viewed as a metapopulation with the ponds being the complex of sources and sinks (sensu, Pulliam, 1988; Weins, 1996) imbedded in the forest ecosystem.

Adults and successful metamorphs move away from breeding ponds as far as 162 m in South Carolina (Semlitsch, 1983) and 286 m (mean = 60.5) in New York (Madison & Ferrand, 1998). We do not know how far adults and juveniles move from breeding ponds in this area but if distances are within these published values, then the entire area encompassing the entire sinkhole pond complex may be used. The entire sinkhole pond complex, ponds and forest, should be protected by another buffer of substantial size, visitors to the area should be prevented from riding off-road-vehicles in the ponds and forest, and protection of individual salamanders from poaching should be strictly enforced. Thus, conservation efforts on behalf of this salamander should focus on maintenance of the natural hydrology of the sinkhole ponds and protection of the entire hardwood forest ecosystem encompassing the SVSP system.

15. *Gyrinophilus porphyriticus porphyriticus* (Northern Spring Salamander) (Spring Pond)

A single larva of this salamander was collected in Spring Pond on 11 July 1986 by H.P. Whidden (USNM 347895).

16. *Hemidactylium scutatum* (Four-toed Salamander) (Ponds 2, 18)

Single individuals have been found near two separate ponds under logs on 7 May 1995 (Hayslett, 1995) and 21 September 1997 (30 mm SVL, 59 mm total length, 0.6 g). This species is usually associated with sphagnum moss and may be more widespread within the SVSP system.

17. *Notophthalmus viridescens viridescens* (Red-spotted Newt) (Ponds 2, 3, 8, 11, 12, 13, 16, 17, 21, 23, 24, 25, 27, 32, 33, 35, Maple Flats North and South, Quarles, Spring Pond)

Newts are commonly encountered in many of the sinkhole ponds. The first adults and larvae from the area were collected from Maple Flats North & South ponds, Spring Pond, and Ponds 11 & 12 on 11 and 18 July 1986 (USNM 347875-77, 347896-900). Adults have been observed in ponds January - October. We observed mating on 6 and 22 February and 6, 23, and 24 March. Larvae were recorded between 17 May and 27 September. Four larvae averaged 19.3±1.9 mm SVL (16-21) on 17 May, 28 larvae averaged 14.4±2.0 mm SVL (11-18) on 14 August, and 9 larvae averaged 15.2±1.3 mm SVL (14-17) on 7 October. One large larva was observed in Pond 12 and one from Pond 13 measured 28 mm SVL on 27 April 1988. These data suggest that some individuals may overwinter in some ponds and reach metamorphosis the year following hatching. Three other larvae caught the same day measured 11-16 mm SVL (mean = 14.3 mm). We found terrestrial efts on 19-21 September. Eight efts measured

27-40 mm SVL (mean 34.6±3.9) and three weighed 1.4-2.1 g (mean 1.7±0.4) on 21 September. We found an adult male under a sphagnum mat on 28 June 1990 at a dry pond. In October 1997 and 1998, we found recently metamorphosed larvae and mature adults under logs and rocks on the dry, exposed rim of ponds that had nearly dried. On 28 May 1997, one adult 44 mm SVL female had a leech attached to her venter (probably the blood leech *Batrachobdella picta* Verrill, Gill, 1978a,b) that left a 4x6 mm lesion when it was removed. Males averaged slightly larger than females: male SVL mean = 43.7±3.6 mm, 34-50, n = 46, female SVL mean = 41.5±5.5 mm, 35-54, n = 41; male mass mean = 2.7±0.4 g, 2.2-3.5, n = 27, non-gravid female mass mean = 1.9±0.6 g, 1.1-2.6, n = 11). Gravid female body mass averaged 3.7±1.1 g (2.5-5.2, n = 5).

18. *Plethodon cinereus* (Red-backed Salamander) (Ponds 2, 11, 12, near 13, 26, 27, 29)

We found most individuals of this terrestrial salamander at several terrestrial locations in the SVSP system between 13 April and 15 October. One was found under a log at Pond 13 on 19 February 1997. Adults have been uncovered under logs in the dry basins of Ponds 27 and 29 on 24 March 1995 and Pond 29 on 27 April 1988.

19. *Plethodon cylindraceus* (White-spotted Slimy Salamander) (Pond 29)

This species was uncommon in the forest in SVSP system. Most of the six individuals were caught in drift fence/pitfall arrays in spring 1988. Other dates of observation were in May and September following rains. Several individuals were found under rocks in the basin of Pond 29 on 27 April 1988. One 87 mm SVL female contained a carabid beetle in her stomach.

20. *Pseudotriton ruber ruber* (Northern Red Salamander) (near Ponds 2, 3, 13)

Several individuals were found under logs and in drift fence/pitfall arrays near some of the sinkhole ponds, although this species is not known to breed in the sinkhole ponds. Dates of observation were recorded in May, September, and October following rains. Five individuals measured 51-71 mm SVL (mean = 62.1±8.7); body mass was 3.2-8.6 g.

Turtles

21. *Chelydra serpentina serpentina* (Eastern Snapping Turtle) (Ponds 2, 8, 10, 13, 14, 33, Maple Flats North and South, Spring Pond)

This large omnivorous turtle has been observed in several ponds but only as an infrequent visitor. Ponds may serve as occasional foraging areas. The two individuals found in Pond 14 may have originated in nearby Spring pond, as this is the only pond in the area that could support a permanent population. Dates of observations are 25 March, 8 & 21 April, 12 May, and 3 & 12 June. The earliest observation was of an active individual in a pond with partial ice cover. The largest individual measured was 297 mm carapace length and the smallest was 196 mm. One nest cavity was discovered between the two Maple Flats ponds on 3 June 1994. It had been opened and the eggs eaten by an unknown mammalian predator.

22. *Chrysemys picta picta* (Eastern Painted Turtle) (Ponds 2, 11, 12, 13, 14, 20, 21, 32, 33, 34, 35, Kennedy Mountain Meadow, Maple Flats North and South, Spring Pond)

Adult painted turtles (n = 16) were observed occasionally in several ponds, especially during night surveys for salamanders. Only Quarles and Spring Ponds may support permanent populations. We have observed several painted turtles sitting on the bottom of ponds in winter. One female caught on 20 January 1990 had a body temperature of 6.7° C, equal to that of the water. One female was found as she was constructing a nest between the two Maple Flats ponds on 3 June 1994. This female was subsequently recaptured in Pond 2 on 6 March 1996 at the same body size. Adult males are smaller than adult females in carapace length, plastron length, and body mass (Table 1).

23. *Clemmys guttata* (Spotted Turtle)

Locations for this species are not provided because of its special concern status. We have found this semiaquatic turtle in several ponds in the SVSP system between late March and early July. All were mature adults (Table 1). Number of yellow spots on the carapace averaged 40.1±14.6 (7-60, n = 17). We have observed movement of individuals between two complexes of ponds, a distance of 2.5 km, and we suspect that most individuals move overland extensively when ponds dry seasonally. Spotted turtle populations are apparently rare in the Shenandoah Valley (Mitchell, 1994; Mitchell & Reay, in press). Because they are so closely tied to shallow, natural, freshwater wetlands, they are threatened range wide by habitat loss, and because they are popular in the pet trade, they are threatened by commercial collection (Ernst et al., 1994). Thus, as with many of the amphibians and reptiles,

Table 1. Body size measurements and pond locations for marked snapping turtles (*Chelydra serpentina*), painted turtles (*Chrysemys picta*), and spotted turtles (*Clemmys guttata*) in the SVSP system, Augusta County, Virginia. Location is pond name or number. Abbreviations: CL = carapace, PL = plastron length, MFN = Maple Flats North Pond, and Spr = Spring Pond. Date is day/month/year. Averages do not include juveniles or recaptures. Measurements are in mm and mass is in grams. Pond locations for *C. guttata* are not provided due to the conservation status of this species.

No.	Date	Pond	Sex	CL	PL	Mass	Notes
				Chelydra serpentina			
1	25/03/88	8	male	287.0			
2	25/03/88	10	male	297.0			
3	08/04/88	8	male	196.0			
4	08/04/88	Spr	male	252.0			
5	12/05/88	10	--				
Male average				258.0			
				Chrysemys picta			
1	12/06/87	14	male	110.0	98.8	152	
2	08/03/88	2	male	104.6	96.7	141	
3	31/03/88	11	male	133.1	117.6	264	
4	31/03/88	11	male	114.9	104.9	182	yellow plastron
unmk	27/04/88	13	female	149.0	139.2		high domed shell
40	20/01/90	13	female	134.0	120.0		missing R forefoot
41	20/01/90	13	male	130.0	118.0		
42	20/01/90	13	female	147.0	130.0		
50	02/02/90	13	male	115.6	105.4	190	
50	21/03/90	13	female	141.4	126.8	350	
10	03/06/94	MFN	female	136.8	125.0	379	nesting
10	06/03/96	2	female	136.8	124.3	355	recapture
10	22/02/95	13	male	135.2	123.5	248	missing L rear ft
101	06/03/96	11	female	90.0	84.1	98	3 year old
102	06/03/96	11	female	150.3	137.5	398	red plastron
24	25/06/96	2	male	131.4	123.0	284	
1100	06/02/97	13	female	131.7	123.0	305	
Male average				121.8	111.0	208.7	
Female average				140.0	128.8	357.4	

Table 1. Continued.

No.	Date	Sex	CL	PL	Mass	Notes
			Clemmys guttata			
1	25/03/88	female	100.6	91.6	140	55 spots
2	25/03/88	male	99.8	87.8	128	48 spots
3	25/03/88	juvenile?	86.2	78.9	87	32 spots
4	29/03/88	male	106.0	92.3	158	31 spots
5	29/03/88	female	101.1	92.3	151	43 spots
6	30/03/88	female	109.1	98.9	166	40 spots
7	30/03/88	female	105.0	96.0	152	34 spots
8	30/03/88	male	104.7	89.6	136	15 spots
9	30/03/88	female	110.7	99.9	189	55 spots
10	31/03/88	male	105.2	91.0	145	45 spots
11	12/05/88	male	113.9	99.3	169	7 spots
12	12/05/88	male	115.6	97.5	165	58 spots
13	12/05/88	male	99.0	81.1	110	41 spots
14	07/06/88	female	106.0	–	–	41 spots
15	07/88	–	109.0	96.0	–	50 spots
100	23/03/95	male	101.2	85.0	139	27 spots
101	23/03/95	female	116.6	106.4	222	60 spots
Male average			105.6	90.5	143.8	34.0
Female average			107.0	97.5	170.0	40.1

the entire SVSP complex is an important area for the conservation of this species in the Shenandoah Valley.

24. *Terrapene carolina carolina* (Eastern Box Turtle)

Shells of this terrestrial species have been found near Twin Pond and Pond 10. On 19 September 1994 between Ponds 2 and 16, we observed two males that had apparently been engaged in combat. One was on its back in a small area in which the leaves had been scattered and trampled. The second, upright, male was about a 0.5 m away. No females could be found. Male aggression has been observed in other areas (Stickel, 1989; Ernst et al., 1994) but this is the first report of one male being overturned during the conflict.

Snakes

25. *Carphophis amoenus amoenus* (Eastern Wormsnake)

A single adult was found on 17 May 1988 at the parking area along the Coal Road adjacent to Maple Flats complex.

26. *Coluber constrictor constrictor* (Northern Black Racer)

One adult black racer was observed swimming across Pond 13 on 21 April 1989. It disappeared under water after swimming to the center of the pond.

27. *Crotalus horridus* (Timber Rattlesnake)

One adult male was caught by Bob Glasgow (Wildlife Biologist, GWNF) in a small field near Spring Pond on 7 June 1987. No others have been seen in the SVSP system.

28. *Diadophis punctatus edwardsii* (Northern Ring-necked Snake)

Several ring-necked snakes have been found under bark or in stumps around the edge of sinkhole ponds. Observations include an unsexed adult (255 mm SVL, 5.1 g) caught on 27 April 1988, a gravid female (264 mm SVL) containing three eggs under tree bark on 28 May 1997, and a juvenile (135 mm SVL, 1.6 g) collected under a log on 14 June 1994. Five adults (2 females, 3 males) were found under bark of standing dead pine and oak trees on 6 July 1998. Adult female snakes (275.5±18.8 mm SVL, n = 4; 6.4±1.3 g body mass, n = 3) averaged slightly larger in length than male snakes (247.7±10.0 mm SVL, 6.7±0.2 g, n = 3). All individuals caught had complete yellow/orange collars, immaculate yellow venters, and uniform gray dorsal regions.

29. *Nerodia sipedon sipedon* (Northern Watersnake) (Ponds 2, 11, 12, 13, 26, 32, 33, 34, Maple Flats North and South)

Northern watersnakes were the most common snake encountered in the SVSP system. Individuals were observed in all months from 13 April to 12 September. Northern water snakes are occasional visitors to sinkhole ponds where they forage on seasonally abundant prey. They seem to appear at times when some prey are especially vulnerable. Several individuals were found preying on *Ambystoma tigrinum* larvae when water levels were very low and the salamanders were concentrated in a small area. One immature male watersnake (117 mm SVL, 13.3 g) disgorged a female *Acris crepitans* (25 mm SVL, 1.45 g). Another juvenile (172 mm SVL, 5.8 g) ate a metamorphic *A. opacum*. The largest adult we measured was a female (670 mm SVL, 276 g).

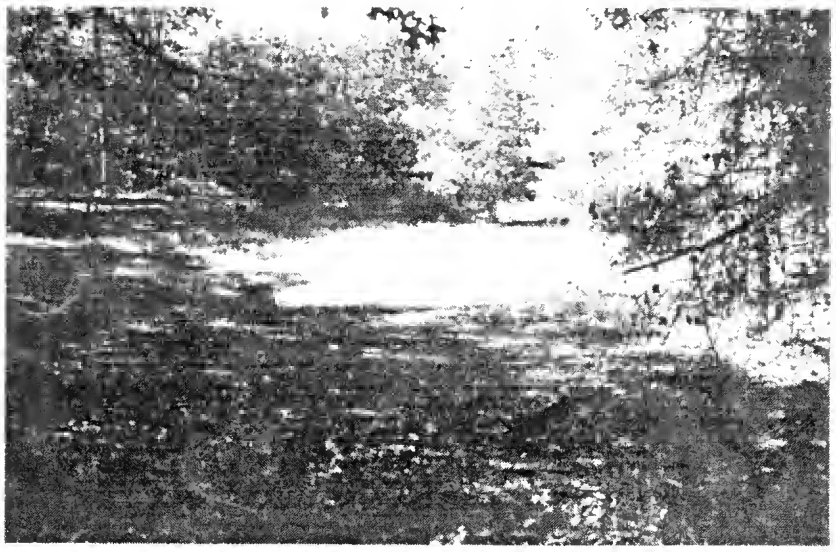
30. *Thamnophis sauritus sauritus* (Eastern Ribbonsnake) (Ponds 3, 11, 13)

Four individuals have been recorded from three ponds. We captured a juvenile on a dry algal mat at Pond 11 on 20 September 1992. Others include a female (23 g) in a grassy area of Pond 3 on 19 September 1995, a juvenile (189 mm SVL, 3.0 g) under a sphagnum mat on 14 October 1995, and a juvenile (229 mm, 4.0 g) found on the trail adjacent to the Maple Flats North Pond on 2 June 1998.

DISCUSSION

The modern herpetofauna of the Shenandoah Valley sinkhole ponds system is comprised primarily of species distributed widely in eastern North America, however, it also includes a small number of habitat specialists and one apparent relic from Pleistocene times. All of the amphibians and reptiles recorded for this area are known to occur in other locations in the mid-Atlantic region (Tobey, 1985; Mitchell, 1994; Conant & Collins, 1998; Mitchell & Reay, in press). Most frogs that occur in the SVSP system breed early in the season or have short larval periods (*Acris*, *Bufo*, *Hyla*, *Pseudacris*, *Scaphiopus*, *Rana sylvatica*). Pond-breeding salamanders include three species in the genus *Ambystoma*, one *Hemidactylium*, and one *Notophthalmus*. Other salamanders in the area include two streamside species (*Gyrinophilus porphyriticus*, *Pseudotriton ruber*) and two terrestrial species (*Plethodon cinereus, P. cylindraceus*). Thus, the total salamander fauna that actually use the sinkhole ponds include three genera and five species. Of the four freshwater turtles known for the area, one is terrestrial (*Terrapene*) and two (*Chelydra* and *Chrysemys*) are occasional users of the seasonal pond habitat. The spotted turtle is the only turtle that appears to be dependent on the seasonal pond habitat for its persistence in this landscape. Only one of the six snake species (*Nerodia*) uses the pond environment on a regular basis and no lizards have been seen here. If the sinkhole ponds did not exist on the alluvial plains in this portion of the Shenandoah Valley, the herpetofauna would probably consist of the recorded two species of toads (*Bufo*), two stream-breeding frogs (*R. clamitans*, *R. palustris*), two terrestrial salamanders (*P. cinereus, P. cylindraceus*), two streamside salamanders (*Gyrinophilus, Pseudotriton*), one turtle (*Terrapene*), and five species of terrestrial snakes. Thus, the sinkhole ponds themselves represent a critical habitat for a substantial portion of the area's known herpetofauna.

The largest data sets on the herpetofauna of the area exist for several of the ponds in the Maple Flats sinkhole pond complex. The rest of the ponds in this complex and all of the ponds in the other two complexes have been visited only a limited number of times (Buhlmann et al., 1999). Much additional work remains to be done before the inventory of the herpetofauna of the SVSP system can be considered complete. Buhlmann et al. (1999) discussed how amphibians and reptiles that inhabit the SVSP system interact with the surrounding landscape. However, the ecology, life histories, and population dynamics of all species need further study before we will understand how they respond to changes in the landscape. We have some information on life history attributes of the ambystomatid salamanders and the spotted turtle (JCM and KAB, unpublished), but we need more data on movement patterns of individuals between ponds. Such information would allow a better understanding of what types of terrestrial habitats are critical to the survival of these animals in this system and how much of the surrounding landscape needs to be included in management and conservation efforts.

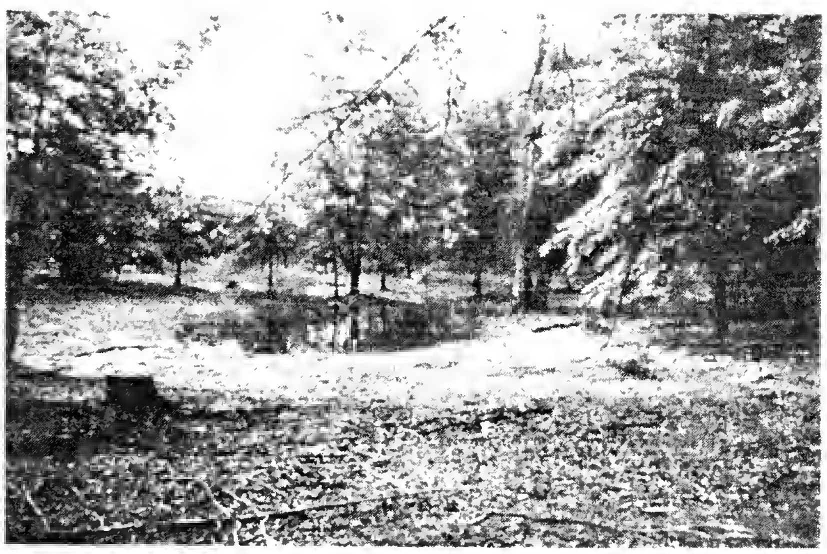


17 October 1998.

21 January 1988.

7 February 1992.

17 May 1988.



21 June 1988.

18 January 1989.

Fig. 4. Annual and seasonal variation in standing water levels in one of the Shenandoah Valley sinkhole ponds, Augusta County, Virginia. (Upper left by T.D. Tuberville. Other photos by KAB.)

Survival of the wetland dependent amphibians and reptiles in the SVSP region cannot occur without the entire complex of ponds. No single pond supports any one species fully. Some ponds are highly seasonal and hold water only in late winter to mid- or late-spring in most years (e.g., Ponds 3 & 14), while others may hold water throughout the summer in wet years (Ponds 2, 17), and still others seldom dry (e.g., Pond 13). Variation in amount and timing of annual rainfall (especially in winter and spring) induces dramatic variation in pond hydrologies. Elevation may play a role because the height of the water table in the alluvial plain varies seasonally with rainfall amounts. Some ponds higher in elevation (Ponds 2, 16) dry earlier than ponds lower in elevation (Ponds 11, 12, 13) (JCM, personal observation). Amphibian species that breed in several ponds simultaneously risk mortality in some but not all of them, whereas those that limit reproduction to a small number of ponds risk low survivorship in all but the wettest years. Several species of amphibians, especially salamanders in the genus *Ambystoma*, have experienced reproductive success in some ponds and reproductive failure in others during the years we have worked in this area (Buhlmann et al., 1999). Loss of individual ponds in the complex would place most species at risk. Adult tiger salamanders may live less than a decade in this area (Buhlmann & Mitchell, unpublished) and repeated unsuccessful reproduction in some ponds due to early drying could cause population decline or loss. Annual variation in rainfall and patterns of pond drying influence population persistence and stability for the pond-dependent amphibians.

Metapopulations consist of distinct units (subpopulations) that may be separated geographically but are connected by dispersal of individuals (Pulliam, 1988; Pulliam & Danielson, 1991). Several of the pond-dependent species in the SVSP system may exist as metapopulations, although the necessary mark-recapture data needed to demonstrate movements are lacking. Pulliam (1988) described the source/sink hypothesis in which some habitats (e.g., ponds), termed sources, produce a surplus of individuals that result in population growth. Other habitats may be sinks that produce no population recruits in bad years. Subpopulations in these sink habitats would become extirpated if immigration from source populations ceased to occur. However, in years of favorable conditions (e.g., adequate hydroperiods) sink habitats may act as source habitats. In the Maple Flats complex, we consider Pond 13 a source habitat and Ponds 2, 3, 5, 14, and 16 sink habitats. Taken together, all ponds in each of the complexes and the entire SVSP system itself act as a dynamic source/sink system. It is clear that protection of the entire complex is required for long-term persistence of a large component of the herpetofauna, including the two rare species.

Acid precipitation is a potential complicating factor for amphibians using the sinkhole ponds for reproduction. Most of the Shenandoah Valley sinkhole ponds are acidic and some have pH values that reach critical levels (Downey et al., 1999). Pond-dwelling amphibians exhibit behavioral, feeding, and altered predator responses and mortality when pH reaches 4.5 or below (Freda & Dunson, 1985, 1986; Dunson et al., 1992; Kutka, 1994). Persistent acid levels below pH 4.5 in ponds during periods in which amphibian eggs and larvae are present would cause severe mortality and result in unsuccessful reproduction. If such conditions lasted for several consecutive years exceeding the life spans of mature adults, then amphibian populations in the SVSP system could decline severely or become extirpated. Downey et al. (1999) demonstrated that pH levels in some ponds with tiger salamanders dip below 5.0 in January and February during which time egg laying and hatching occur. Tiger salamanders and other species of amphibians may be at risk from anthropogenic sources of acid precipitation. Clearly, ponds in the SVSP system need to be monitored on a regular basis and management plans need to be developed to minimize the effects of this threat.

The herpetofauna of the SVSP system in the Big Levels area would not be as rich without the sinkhole pond wetlands. Nor would it be as rich if the landscape in which these ponds are imbedded did not support a forest habitat suitable for these animals. The future of the amphibian and reptile populations in this area, especially the state endangered tiger salamander, depends on the long-term persistence, protection, and management of both habitat types.

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Observations on Small Mammals in the Maple Flats Sinkhole Pond Complex, Augusta County, Virginia

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INTRODUCTION

The Big Levels area, consisting of a series of sinkhole pond complexes, provides a unique habitat for plants (Fleming & Van Alstine, 1999) and animals (Buhlmann et al., 1999). The largest Virginia population of the state endangered tiger salamander (*Ambystoma tigrinum*) breeds in these ponds (Mitchell & Buhlmann, 1999). The permanent ponds in Maple Flats also support the third richest site of dragonflies and damselflies currently known in Virginia (Roble, 1999). The unique flora and fauna of the area are directly associated with the sinkhole ponds and immediate terrestrial habitats. Efforts to document small mammal assemblages in the sinkhole pond area are previously unreported.

The forests around the sinkhole ponds are comprised of a variety of forest types including oak-hickory, oak-pine, pitch pine, and variations of these mixed forest types. These forests have been actively managed over the past 50 years and the age structure reflects management practices with stands ranging from early succession to mature forests. With the U.S. Forest Service designating the Maple Flats Sinkhole Pond complex as a Research Natural Area, future forest management within the complex is expected to be minimal and the forest should ultimately reach maturity. We sampled the small mammal community associated with maturing oak-hickory/pitch pine forests adjacent to several sinkhole ponds and report preliminary observations on small mammal species richness, diversity, and demography.

MATERIALS AND METHODS

In summer 1998, from mid-June to mid-August, 100 Sherman live traps were placed in two 5x10 grids with 15 m spacing between traps. Sherman live traps were run for 2 four-night periods at one grid and 3 four-night periods at the second grid for a total of 1,000 trap nights (TN). Traps were baited with a combination of peanut butter and oats wrapped in wax paper scented with oil of anise. Traps were checked daily during each trapping period. Individuals captured were toe-clipped and data were gathered on age, sex, reproductive condition, presence of parasites, and mass for both previously unmarked and recaptured animals. Three days after the final live-trapping session, snap traps were run for four consecutive nights (400 TN) in order to assess the effectiveness of live traps. Snap traps were baited with peanut butter and placed in the same location as the Sherman traps.

Fifty 2-L pitfall traps were placed in two 5x5 grids with 15 m spacing. Pitfalls were half filled with water. One grid was run for seven consecutive nights in early May, then closed and run from 30 June to 18 August. A second pitfall grid was run from 30 June to 19 August. Pitfall TN totaled 2,600. Traps were checked twice a week and age, sex, reproductive condition, presence of parasites, and mass were recorded for each mammal.

Shrews were dissected to determine reproductive condition. Based on tooth wear, individuals were assigned to one of three age classes: adult = upper incisors heavily worn with little red pigmentation showing, sub-

adult = upper incisors moderately worn with moderate amount of red pigmentation showing, and juvenile = upper incisors sharp with large amount of red pigmentation showing.

Based on pelage color, individual *P. leucopus* were assigned to one of three age classes: adult = brown dorsal and lateral pelage, sub-adults = brown dorsal and gray lateral pelage, and juveniles = gray dorsal and lateral pelage. Body mass was calculated using specimens from snap traps and the initial capture in each sample period for Sherman live traps. Individuals captured in pitfalls were not used in mass calculations due to deterioration and wet pelage. Mass is reported as the mean ± one standard error. We calculated species diversity using the Shannon index (H') and evenness as (J') (Zar, 1996).

RESULTS AND DISCUSSION

A total of 91 individual small mammals was captured using all three trap types. Five species were represented; *Blarina brevicauda, Peromyscus leucopus, Sorex fumeus, Sorex hoyi,* and *Sorex longirostris.*

Peromyscus leucopus

The white-footed mouse occurs in many habitat types. Studies in the Virginia Coastal Plain (Mitchell et al., 1993), Piedmont (Pagels et al., 1992), and Ridge and Valley physiographic provinces (Mitchell et al., 1997) have documented *P. leucopus* as the most abundant rodent in all of these areas. We captured 15 individual *P. leucopus* a total of 39 times in Sherman live traps, 21 individuals in snap traps, and 4 individuals in pitfall traps. Of the 21 individuals captured in snap traps, 11 were originally captured in Sherman live traps, 9 were new captures, and one was partially consumed. Captures per unit effort are given in Table 1.

Initial captures included 26 males and 13 females, yielding a sex ratio of 2.0 males/female. Of the adults captured, 16 were males and 9 were females, yielding an adult sex ratio of 1.8 males/female. Total sub-adult captures included 6 males and 4 females, yielding a sub-adult sex ratio of 1.5 males/female. Four juvenile males and no juvenile females were captured. In each age group, males were captured more frequently than females. The overall sex ratio of 2.0 males/female is statistically different from 1:1 ($X^2 = 4.3$, $P < 0.5$) and suggests that males were more abundant or more likely to be captured than females.

Based on pelage color, 25 of the *P. leucopus* were adults, 10 were sub-adults and 4 were juveniles. Of the adults, 10 were females, yielding a juvenile to adult female ratio of 0.4 juveniles/adult female.

Based on enlarged testes, 8 of 20 adult male *P. leucopus* were reproductively active. Six of 10 adult females were reproductively active based on perforate vaginae. Reproductive activity was first observed in males in August and in July for females. The vaginal condition of females in July suggested that males were potentially active at or before this period also.

Body mass of adult males was 23.8 ± 2.26 g (n = 19, range = 19.9 - 27.7) and for adult females was 24.4 ± 5.58 g (n = 7, range = 15.5 - 32.6). Some of the variance in adult female mass may be attributed to weight gains associated with pregnancy. Body mass of sub-adult males was 19.0 ± 4.4 g (n = 5, range = 12.1 - 23.8) and for sub-adult females was 18.7 ± 2.09 g (n = 4, range = 16.3 - 21.4). Body mass of juvenile males was 15.5 ± 2.14 g (n = 4, range = 13.1 - 17.9). No juvenile females were captured.

Five of the 15 *P. leucopus* captured showed signs of botfly (*Cuterebra* sp.) parasitism. All were observed between 12 and 19 August. Hensley (1976) found botfly parasitism to peak in August for *P. leucopus* from Rockingham, Shenandoah, and Augusta counties, Virginia.

Sorex hoyi

Until the late 1980s, the pygmy shrew was considered one of the rarest shrews in Virginia. Pagels (1987) extended the known localities to 22. Since then the pygmy shrew has been collected in numerous localities, and in some instances has been found to be relatively abundant.

We captured 15 individual *S. hoyi* in pitfall traps. The capture ratio was 0.56/100 trap nights (Table 1). Of the total captures, 3 were males, 10 were females, and 2 were unidentified, yielding a sex ratio of 0.3 males/female. Although females were more abundant or more likely to be captured than males, the observed sex ratio was not statistically different from 1:1 ($X^2 = 3.77$, $P > 0.05$).

Of the total individuals captured, 5 were adults, 8 were sub-adults, and 2 were juveniles, based on tooth wear. Of these, 3 were adult females yielding a juvenile to adult female ratio of 0.67 young/adult female. Reproductive condition could only be determined for one individual, a reproductively active male.

Due to the small sample size, we calculated mean mass by age class only. Body mass for adults was 3.1 ± 0.16 g (n = 5, range = 2.9 - 3.3), 2.8 ± 0.4 g for sub-adults (n = 8, range = 2.0 - 3.4), and 2.5 ± 0.07 g for juveniles (n = 2, range = 2.0 - 2.1).

Table 1. Species, individuals captured, and trap success (number/100 trap nights in parenthesis) by trap type and species richness at Maple Flats Sinkhole Pond complex, Virginia, 1 May - 19 August, 1998.

	Trap Type		
Species	Sherman Live	Snap	Pitfall
Peromyscus leucopus	15 (3.9)	21 (5.3)	4 (0.15)
Sorex hoyi	----	----	15 (0.56)
Sorex longirostris	----	----	7 (0.26)
Sorex fumeus	----	----	1 (0.037)
Blarina brevicauda	----	3 (0.75)	1 (0.037)
Total (#/100 Trap Nights)	39 (3.9)	24 (6.0)	28 (1.05)
Richness	1	2	5

Sorex longirostris

Like the pygmy shrew, the distribution of the southeastern shrew was little known until the 1980s. Pagels et al. (1982) summarized records from the District of Columbia, Maryland, and Virginia and reported 11 observations in the Coastal Plain, 24 in the Piedmont, and two in the Ridge and Valley Province. Additional work by Pagels & Handley (1989) increased the range of this species in Virginia to include the Blue Ridge and Cumberland Plateau Physiographic Provinces. Today, the southeastern shrew is known to have a statewide distribution below 600 meters, except for the Eastern Shore where it has not been reported.

We captured 7 individual *S. longirostris* in pitfall traps. The capture rate was 0.26/100 trap nights (Table 1). Total captures included 5 males and 2 females, yielding a sex ratio of 2.5 males/female. Similar to *P. leucopus*, these data suggest that males were more abundant or more likely to be captured than females. The observed sex ratio was not statistically different from 1:1 ($X^2 = 1.29$, $P > 0.25$).

Based on tooth wear, one individual was an adult, three were sub-adults, and three were juveniles. Reproductive activity was not evident for any of the specimens.

Due to the small sample size, we calculated mass by age group only. Individual adult mass was 3.9 g. Mean body mass for sub-adults was 3.4 ± 1.01 g (n = 3, range = 2.2 - 4.0), and mean body mass for juveniles was 2.9 ± 0.35 g (n = 3, range = 2.5 - 3.1).

Sorex fumeus

The smoky shrew is a common and relatively abundant shrew in the mountains of Virginia. In our study, we captured only one *S. fumeus* in a pitfall trap. This individual was a sub-adult female with a mass of 5.6 g.

Blarina brevicauda

The northern short-tailed shrew is considered one of the most abundant small mammals in Virginia and it inhabits most terrestrial habitats. We captured four *B. brevicauda*, one in a pitfall trap and three in snap traps. All four animals were adults, two males and two females yielding a 1:1 sex ratio. None of the individuals was reproductively active. Mean body mass of the three captured in snap traps was 15.7 ± 1.7 g (range = 13.7 - 16.7).

Other Mammals Observed

Several other mammal species observed during our study, included white-tailed deer (*Odocoileus virginianus*), gray squirrel (*Sciurus carolinensis*), and runways

of a mole species. The gray squirrel is a common mammal of oak-hickory forests in the eastern U.S. Surprisingly, we observed only one *S. carolinensis* during our field activity. This may be a reflection of a low population, annual variation, or poor site quality to support gray squirrels. Mist netting for bats was conducted on three nights in conjunction with an education program. *Eptesicus fuscus* (big brown bat) and *Pipistrellus subflavus* (eastern pipistrelle) were captured on two of the three nights.

Species Richness, Diversity, and Evenness

Five species of small mammals were captured in the Maple Flats Sinkhole Pond complex. Species richness varied among trapping techniques, pitfall traps captured all 5 species, snap traps captured 2 species, and Sherman live traps captured 1 species (Table 1). Species diversity (H') and Evenness (J') were computed for pitfall captures at 0.699 and 0.744, respectively.

Several studies have described differences in capture success among pitfall traps, Sherman live traps, and/or snap traps (Williams & Braun, 1983, Mitchell et al., 1993, Kalko & Handley, 1993). Our use of all three methods was intended to increase capture success and species diversity. Pitfall traps provided the greatest diversity and species richness while snap traps had the highest capture rate (Table 1). Sherman live traps captured only one species, and the capture rate was intermediate between those for pitfall and snap traps.

Although a direct comparison of capture success, diversity indices, and species richness from other Virginia small mammal studies may not be statistically valid due to differences in sampling efforts, time, habitat differences, and geographical differences, a subjective comparison suggests the Maple Flats Sinkhole Pond complex contains low species richness, diversity, and numbers. Jackson et. al. (1976), sampling with snap traps, reported an overall capture rate of 9.4/100 trap nights at Presquile National Wildlife Refuge and observations of 22 mammal species. Painter & Eckerlin (1993), using snap traps, Sherman, and Hav-a-Hart live traps, did not report capture success, but observed 22 mammal species at the George Washington Birthplace National Monument. Pagels et al. (1992), sampling with pitfall traps, reported species diversity indices greater than 2.0 and species richness greater than 10 for two mixed forest sites in Cumberland County, Virginia. With a species richness of five species, a diversity index of 0.699 and a capture success of 1.05 individuals/100 trap nights (for pitfall traps), the Maple Flats Sinkhole Pond small mammal community appears less rich, diverse, and populated compared to other areas in Virginia. Additional trapping efforts could add to the species list of small mammals occurring in the Maple Flats Sinkhole Pond complex.

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Hydrology and Geomorphology of Green Pond – a High-elevation Depressional Wetland in the Blue Ridge of Virginia

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INTRODUCTION

Green Pond is a sphagnum bog situated on a broad summit in the Blue Ridge Mountains of central Virginia. In this research project, we analyzed the surficial aquifers and groundwater flow system that support this high elevation ecosystem in order to evaluate how water level fluctuations respond to changes in precipitation and evapotranspiration. Such studies provide the hydrogeological data needed for sound ecological management of sensitive environments.

Hydrogeologic Setting

Green Pond (Fig. 1) lies on Big Levels (elevation 976 m), the crest of a northwestward spur of the Blue Ridge Mountains. This upland, named the Greenville Salient by Moore (1952), is deeply incised by steep stream valleys that form the headwaters of the St. Marys River and South River. Immediately north of Flint Mountain, Big Levels plateau is a 600 m wide bench with less than 6 m of topographic relief in the Green Pond area. Green Pond sits within a depressional wetland that possesses no visible inlet or outlet streams; however, during periods of high rainfall, the pond is drained by overland flow to the north along foot trails. Downhill, numerous springs emerge from quartzite talus and bedrock fractures along valley toeslopes.

Groundwater within the study area appears to move through intergranular pores in residuum and sandstone as well as through fractures in quartzite and other bedrock. The Antietam Formation underlies the ridge summit and most of the Greenville Salient. Overall, this unit consists of resistant, thickly and very thickly bedded, white to gray quartzite interbedded with equal amounts of thickly stratified, less resistant sandstone. Subordinate amounts of laminated shale and siltstone (5-10%) and conglomerate (1%) occur throughout the thickness of the unit (Schwab, 1970; Gathright, 1977). Some authors separated the Antietam into an upper member and a lower member based on lithology and outcrop pattern (Moore, 1952; Caskie, 1957; Sweet, 1981). The lower member consists of up to 120 m of white, vitreous quartzite that crops out as ledge or cliff-making beds up to 30 m thick. The upper member of the Antietam consists of buff to brown friable sandstone in beds several cm to meters thick. The upper member generally creates an outcrop pattern of well rounded slopes covered by blocky sandstone and quartzite float.

Porous regolith transmits the shallow groundwater flows on the Big Levels plateau. The geomorphic history of the surficial materials and the characteristics of the rocks that produced them govern the permeability and distribution of shallow aquifers. Thus, we must understand how the landscape on Big Levels developed in order to evaluate the stratigraphic framework of this hydrogeologic setting.

The vast majority of wetlands within the Blue Ridge and adjacent provinces are not depressional but form in slope and riverine settings associated with stream valleys (Brinson, 1993; Smith et al., 1995; Cole et al., 1997). The enclosed basins where depressional wetlands can form in the Blue Ridge might be influenced by several geomorphic processes including periglacial sedimentation (Eargle, 1977; Delcourt & Delcourt, 1985), rotational slump blocks (Schultz & Southworth, 1989), structural controls (Diehl & Behling, 1982), or bedrock solution (Reed et al., 1963). Knechtel (1943) and Werner (1966) suggest that Green Pond is a solutional depression that lies on a small lens of dolomite on the axis of a very gentle syncline. Several problems exist with this interpretation. Stratigraphically, the Tomstown (Shady)

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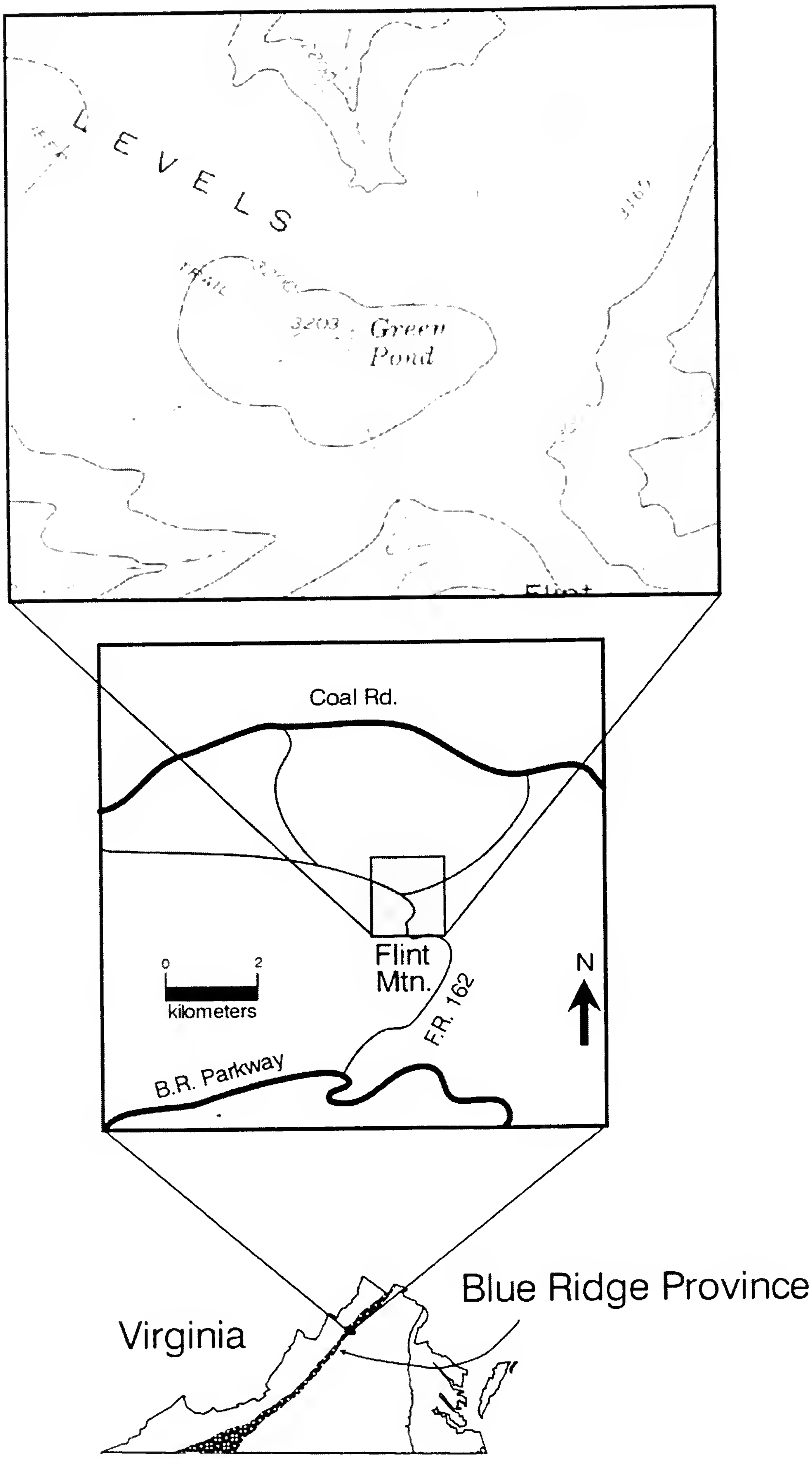

Fig. 1. Location of Green Pond and topographic map of study area. Topography taken from USGS Big Levels quadrangle; contour interval 40 feet. US Forest Service Road 162 intersects the Blue Ridge Parkway at Bald Mountain overlook. Valleys leading away from Big Levels and Kennedy Ridge are headwaters for Kennedy Creek (to the east), Cole's Run (to the north), and St. Marys River (to the west).

dolomite does overlie the Antietam quartzite; thus a dolomite-solutional origin for Green Pond is structurally possible. However, soluble exposures of dolomite are very rare near the surface throughout the region because the unit is usually strongly weathered to saprolitic residuum to depths of 30-60 m (Knetchel, 1943). The shallow dips on the limbs of the syncline mapped by Knetchel (1943) suggest that no soluble dolomite should be expected at depth below Green Pond. Also, based upon the results of three previous geologic studies, the precise geologic pattern of the Green Pond area is open to question - maps made by Knechtel (1943), Moore (1952), and Werner (1966) contain different numbers and locations of geologic structures there. According to Moore (1952), for example, Green Pond formed on quartzite on the limb between two folds.

Reed et al. (1963) suggested that shallow depressions on quartzite ridges in North Carolina, in settings very similar to those found at Green Pond, could have formed by silica solution if the surface was stable for a million years or longer. Noting that the pond waters contained appreciable quantities of dissolved silica, they concluded that acids generated in organic-rich sediments could aid in the long term solution of quartzose rocks and regolith. Bennet & Siegel (1987) and Bennet et al. (1991) demonstrated that in a peat bog the solubility of quartz increases sufficiently to enhance quartz dissolution due to complexing of organic acids.

Hockman et al. (1979) mapped the soils in the study area as the Leetonia Series. This series occurs on broad ridges and side slopes, formed in siliceous materials weathered mainly from the Antietam quartzite. The Leetonia Series has been classified as a sandy, skeletal, siliceous podzol (mesic Entic Haplorthod). The predominant texture of these soils is very stony loamy sand. Wilson (1958) noted that the distinguishing feature of the Leetonia Series in Virginia is the presence of a bleached spodic (E) horizon due to the low base status of the siliceous parent material and the abundant acid vegetation (conifers).

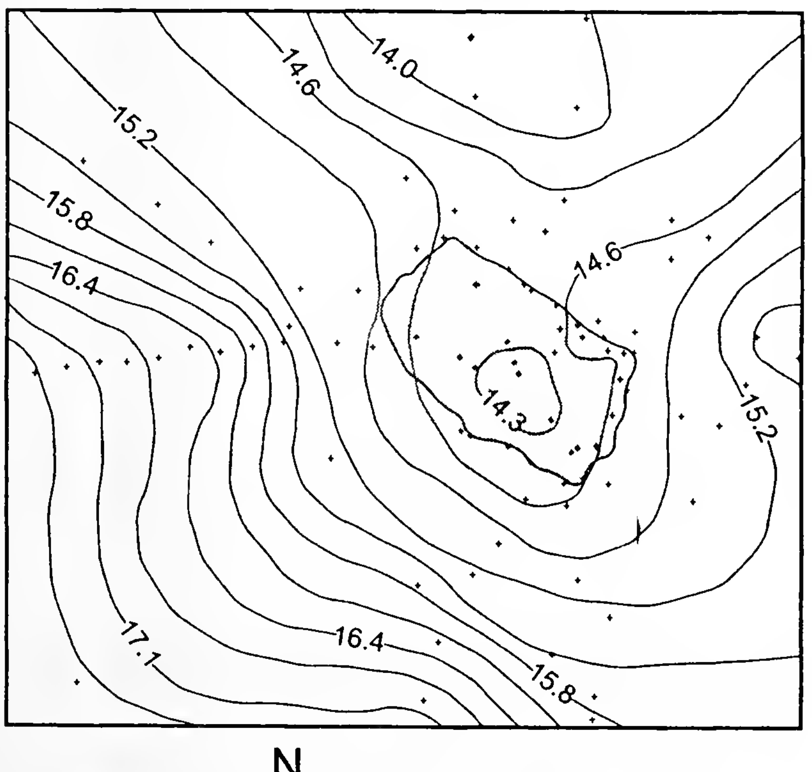

Fig. 2. Topographic map of Green Pond and surrounding area. Contours are in meters above an arbitrary local datum. Crosses indicated locations of surveyed points. Grey area is extent of open area around pond.

Ecologic Setting

Non-alluvial wetlands of the central and southern Blue Ridge exhibit a considerable range of vegetation and wildlife, a diversity driven by the geology, soil, water chemistry and flow, elevation, age, and biogeographic history of the wetland and surrounding setting (Hanenkrat, 1980; Carter, 1986; Weakley, 1991). The Green Pond area is especially unusual, however. The forest surrounding Green Pond that developed in the 40-60 years since the latest clearcutting event is somewhat stunted, probably because of adverse climatic conditions and low soil fertility. It is dominated by pitch pine (*Pinus rigida*), white pine (*Pinus strobus*), black oak (*Quercus velutina*), scarlet oak (*Quercus coccinea*), red maple (*Acer rubrum*) and blighted chestnut (*Castanea dentata*). The understory shrub layer contains abundant mountain laurel (*Kalmia latifolia*) and Catawba rhododendron (*Rhododendron catawbiense*), huckleberry (*Gaylussacia* sp.), and Viburnum. The herb layer consists predominantly of cinnamon fern (*Osmunda cinnamomea*) and greenbrier (*Smilax* sp.) in wetter areas. Vegetation growing on the substrate of the pond consists of a sphagnum mat with numerous grasses and sedges such as *Carex* and the three-way sedge (A. Plocher, personal communication, 1993); several of the obligate wetland species in Green Pond are listed on the Virginia Rare Wetland Species List (C. Ludwig, personal communication, 1991). In the 1930s, a naturalist planted cranberries in the bog (Hanrenkrat, 1980).

True sphagnum bogs, such as Green Pond, are rare in Virginia, as are bogs and fens throughout the central and southern Appalachians (Schafale & Weakly, 1990). Of all the factors that form and sustain these rare ecologic settings, a critical, and maybe predominant, influence is the dynamic balance provided by the local wetland hydrology.

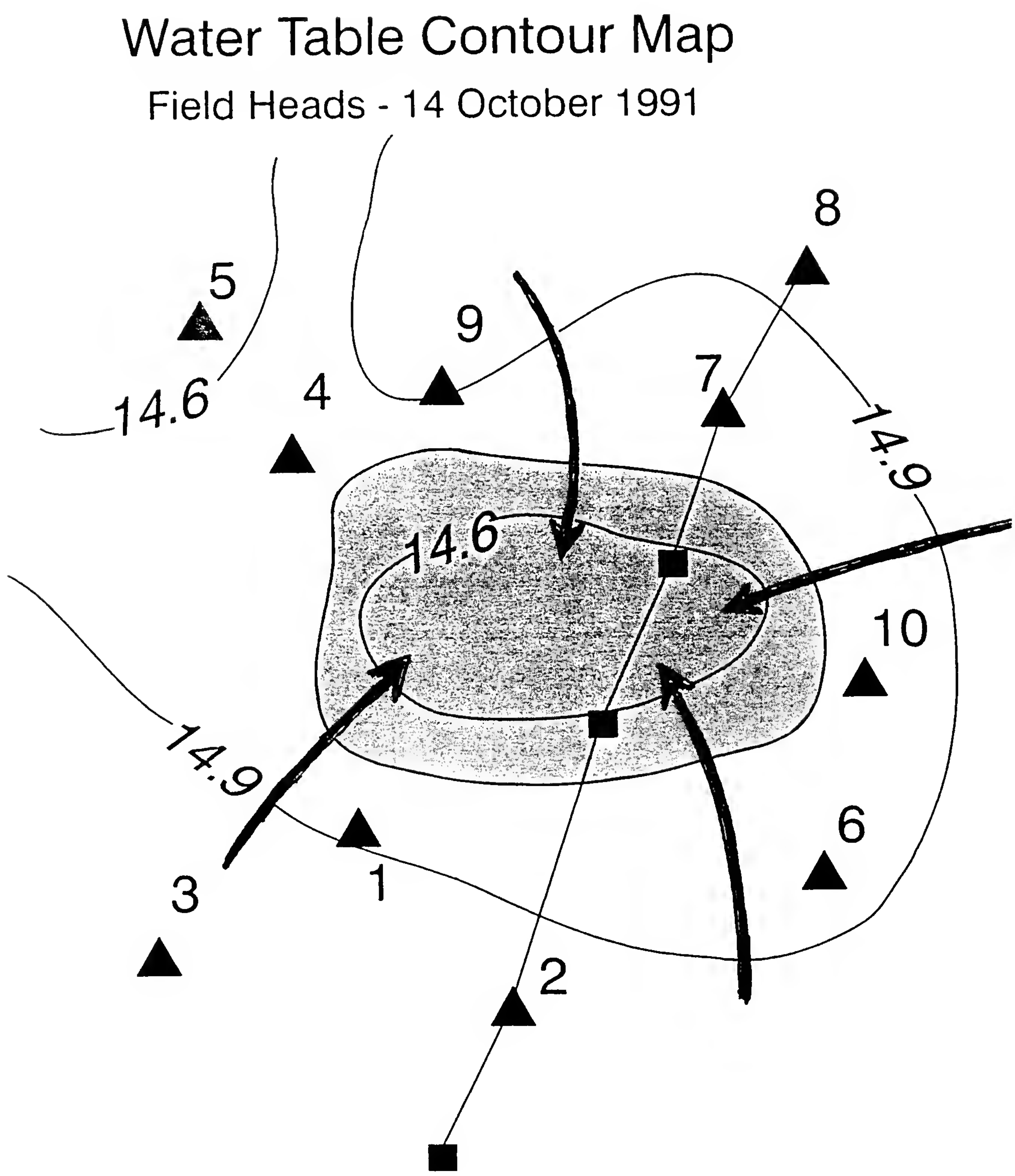

Fig. 3. Water table contour map for the Green Pond area on 14 October 1990. Contoured elevations are in meters above local datum. Triangles mark locations of monitoring wells. Arrows represent directions of groundwater flow. Line marks transect through well sites and boreholes (squares) used in Fig. 4.

FIELD METHODS AND RESULTS

Detailed elevation measurements taken along trails and open areas using a laser-based theodolite allowed us to analyze the surface morphology in and around Green Pond. An arbitrary local datum was set 50 feet (15 m, approximately) below a temporary benchmark. The large-scale (1"=50') topographic map constructed from the survey data (Fig. 2) became the base map for hydrologic analyses. Locations of bedrock outcrops, springs, drainage lines, and other features were plotted at 1:24000 using aerial photographs and U.S.G.S. topographic maps.

Ten groundwater monitoring wells installed around the perimeter of Green Pond permitted measurement of water table fluctuations in the shallow subsurface. We augered the boreholes to 1.5-2.0 m, close to the bedrock-residuum contact, and slotted the well risers along their entire lengths to within 15 cm of the surface. We placed well tops above the pond's seasonal high water mark and surveyed their elevations. Both chalk-and-tape and electronic probe techniques produced water elevation measurements that were repeatable to +0.5 cm. The water

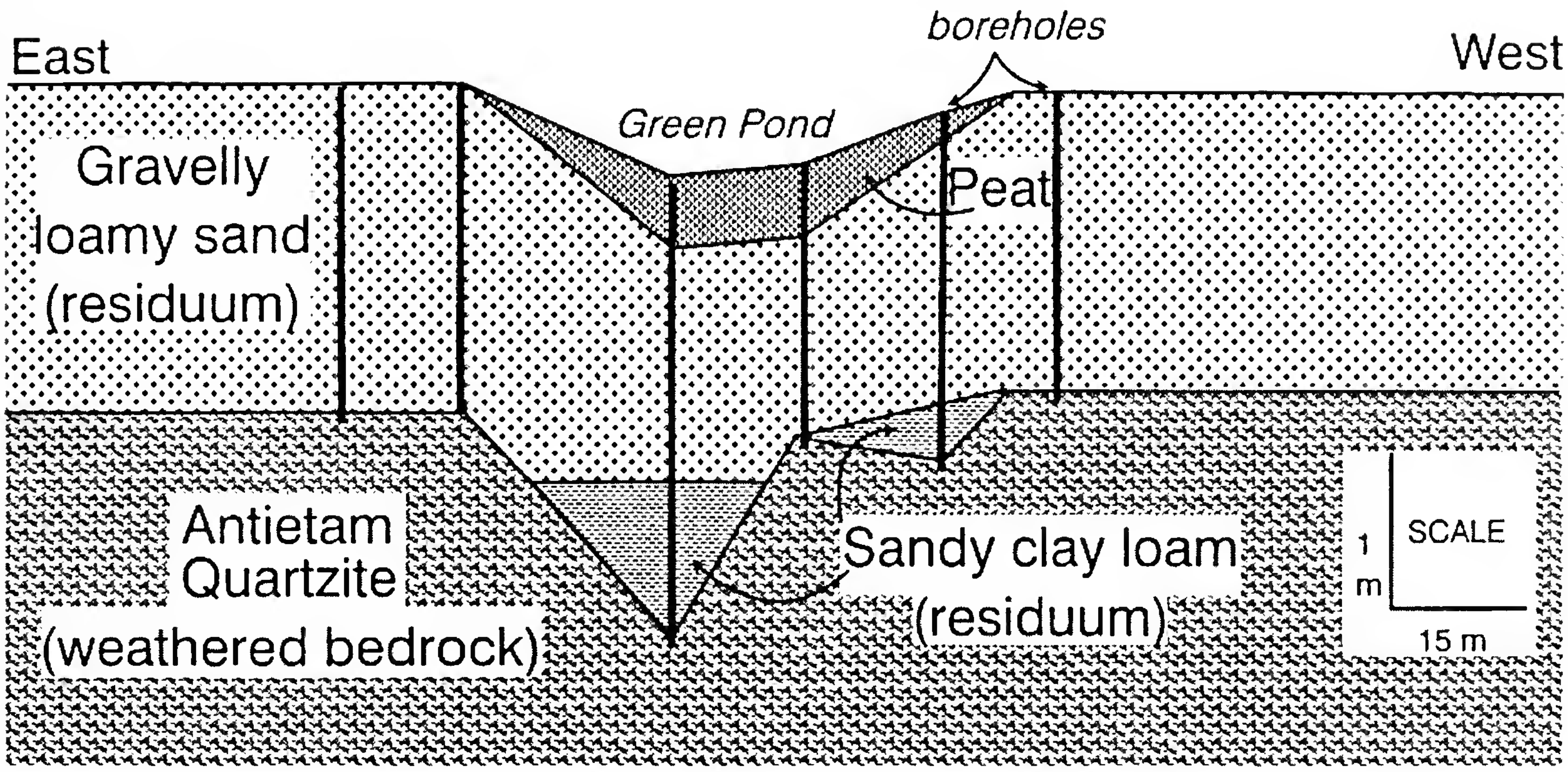

Fig. 4. Diagrammatic cross-section through Green Pond. Borehole locations noted in Fig. 3. In the gravelly sand loam residuum formed from quartzite, the coarsest sediments occur in the bottom 10-20 cm.

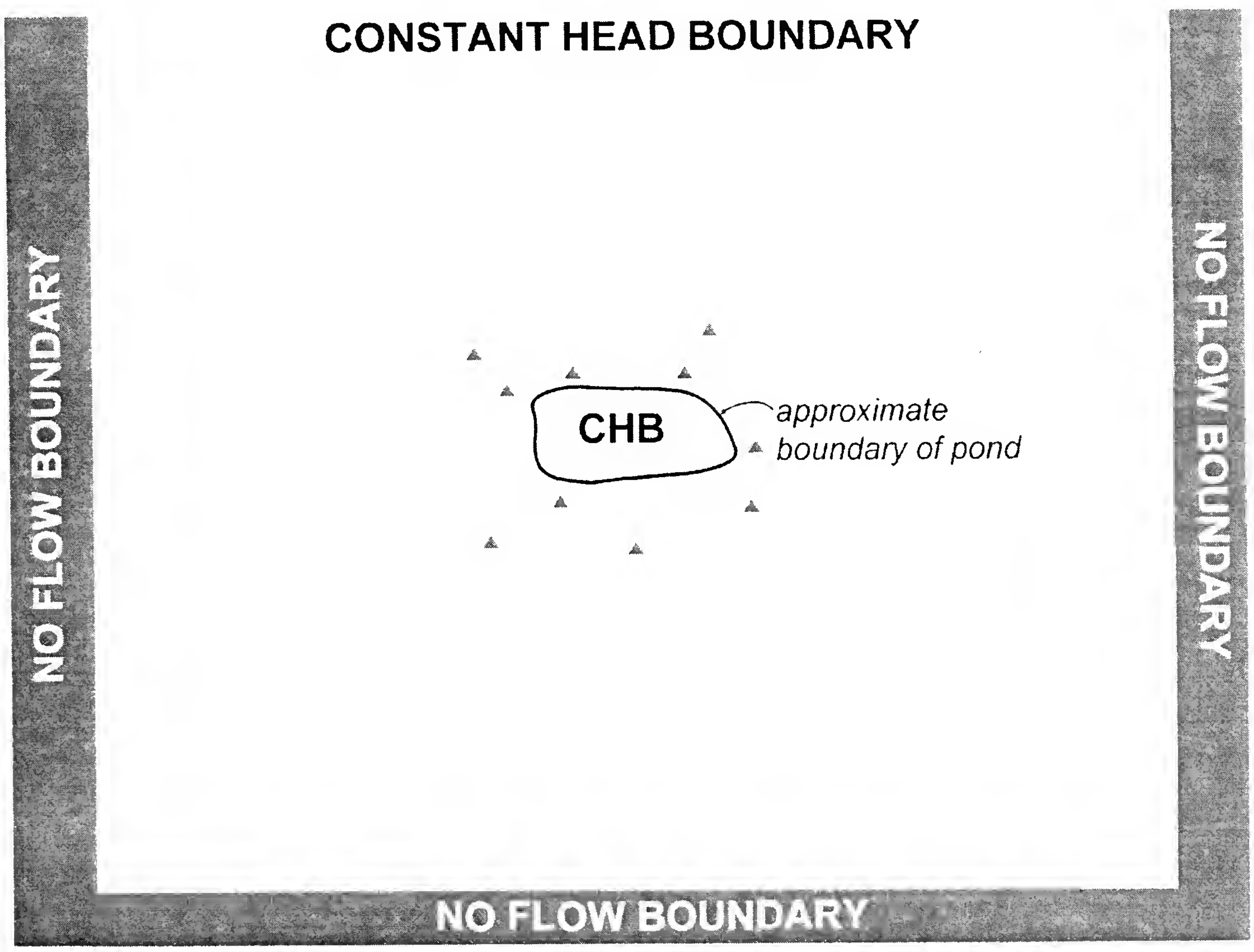

Fig. 5. Cells used for finite-difference groundwater flow model. Constant head boundaries (CHB) and no-flow boundaries noted by shading. Locations of monitoring wells used for calibration marked with triangles.

table maps constructed from these data allowed determination of groundwater flow directions (Fig. 3).

We described sediments taken from eight exploratory hand auger holes drilled along three transects within the clearing of Green Pond (Fig. 3). Data on the depth, Munsell color, texture, mottles, consistency, structure, cementation, and coarse fraction content proved most useful (see Jacobson, 1987 for techniques). The holes were drilled to bedrock, if possible, or to a maximum of 2.25 m; at this depth the overlying weight and pressure of the groundwater on the hand auger severely impeded removal of the auger. Stratigraphic cross-sections show the vertical and horizontal distribution of materials underlying Green Pond (Fig. 4).

We sampled pore water within the peat and underlying mineral material during one day and analyzed it for dissolved silica. Piezometers inserted various depths into the peat collected water that was extracted with a peristalic pump and analyzed in the field using a silica test kit accurate to within 2 ppm. Serial dilutions with deionized water permitted estimations of up to 300 ppm in silica rich areas.

These field data indicate that Green Pond lies in an elongated drainage basin that sits on a plateau underlain by nearly level Antietam quartzite. The land surface generally slopes to the north and overland flow exits the basin during and after some rainstorms through a low portion of the northern drainage divide. Groundwater flows into the pond, draining from a low ridge south of the pond and from the surrounding summit plain (Fig. 3).

Soils on the plateau surrounding the pond are usually less than 2 m thick and mostly consist of gravelly loamy sand to very gravelly sand. Loamy sediments usually occur near the surface, whereas the very gravelly sand is normally near the soil-bedrock interface. These geomorphic and textural characteristics suggest that the soils are residual materials derived from the underlying quartzite and have experienced little if any lateral movement. Peaty deposits up to a meter thick underlie the pond area. In some locations beneath the peat, fine grained mineral soil exists and can be quite clayey, especially in the southwestern portion of the pond area. These zones might be attributed to variations in parent material but their existence only beneath the peaty wetland soils suggests they are residual soil material with a history of more intense weathering, perhaps due to higher concentrations of organic acids. Our reconnaissance grade observations of silica concentrations in pore waters from piezometers 1-2 m away from the pond ranged between 20-300 ppm. Water collected from farther away was much lower. At Observation Well #10, silica concentrations were usually 2.5-3 ppm; springs at the headwaters of Cole's Run and Kennedy Creek averaged 3-4 ppm.

The lack of widespread clays or residual saprolitic dolomite suggests that Green Pond did not form by solution of Tomstown (Shady) dolomite. No direct evidence exists, either, to support a formative hypothesis related to periglacial processes. However, the levels of dissolved silica in groundwater near Green Pond that are an order of magnitude higher than in "background areas" indicate that Green Pond may have formed by dissolution of quartz with the aid of organic acid (e.g., Reed et al., 1963).

HYDROLOGIC ANALYSES

Analytical models or steady-state finite difference models can effectively simulate groundwater flows in some hydrogeological settings. The advantage of these models is that they are relatively simple. Where the geologic setting is relatively uniform and the only source of water is rainfall, the model may consist of only a single equation that relates the profile of the water table to simple estimates of the hydraulic conductivity (K) and geometry of the aquifer and the rate of recharge (W) (e.g. Fetter, 1980; p. 136). If the goal of the model is to describe heads in wells over large areas, a finite difference model can generate a contour map of the water table, but the initial data requirements are equally simple. The largest problem arises in estimating a single "steady state" value to represent recharge, a very "transient" variable. It is easy to obtain recharge estimates based on water budget calculations that use monthly temperature and rainfall data. However, our previous studies have shown that a monthly recharge value (W_{mo}) is insufficient when trying to simulate fluctuating water levels in ponds (Whittecar & Emry, 1992). Antecedent rainfall and evapotranspiration during several months must be incorporated in the calculation of the recharge value used in these simple models. As we will explain, we use a time-averaged recharge value, the "effective monthly recharge" (W_{em}), to overcome this problem.

We used a two-dimensional finite difference aquifer simulation model (PLASM) to analyze the groundwater flow in the Green Pond area (Prickett & Lonnquist, 1971). PLASM operates on a grid of nodes and calculates the discharge of water entering and exiting cells around each node. Each cell carries a value of hydraulic conductivity (K), aquifer thickness (b), and recharge rate (W). PLASM will predict the hydraulic heads that will occur across the area under given conditions. The results of this prediction should closely replicate field-measured heads; if a poor match results, one or more of the models parameters are changed and the model is rerun. This calibration process continues until a match falls within the

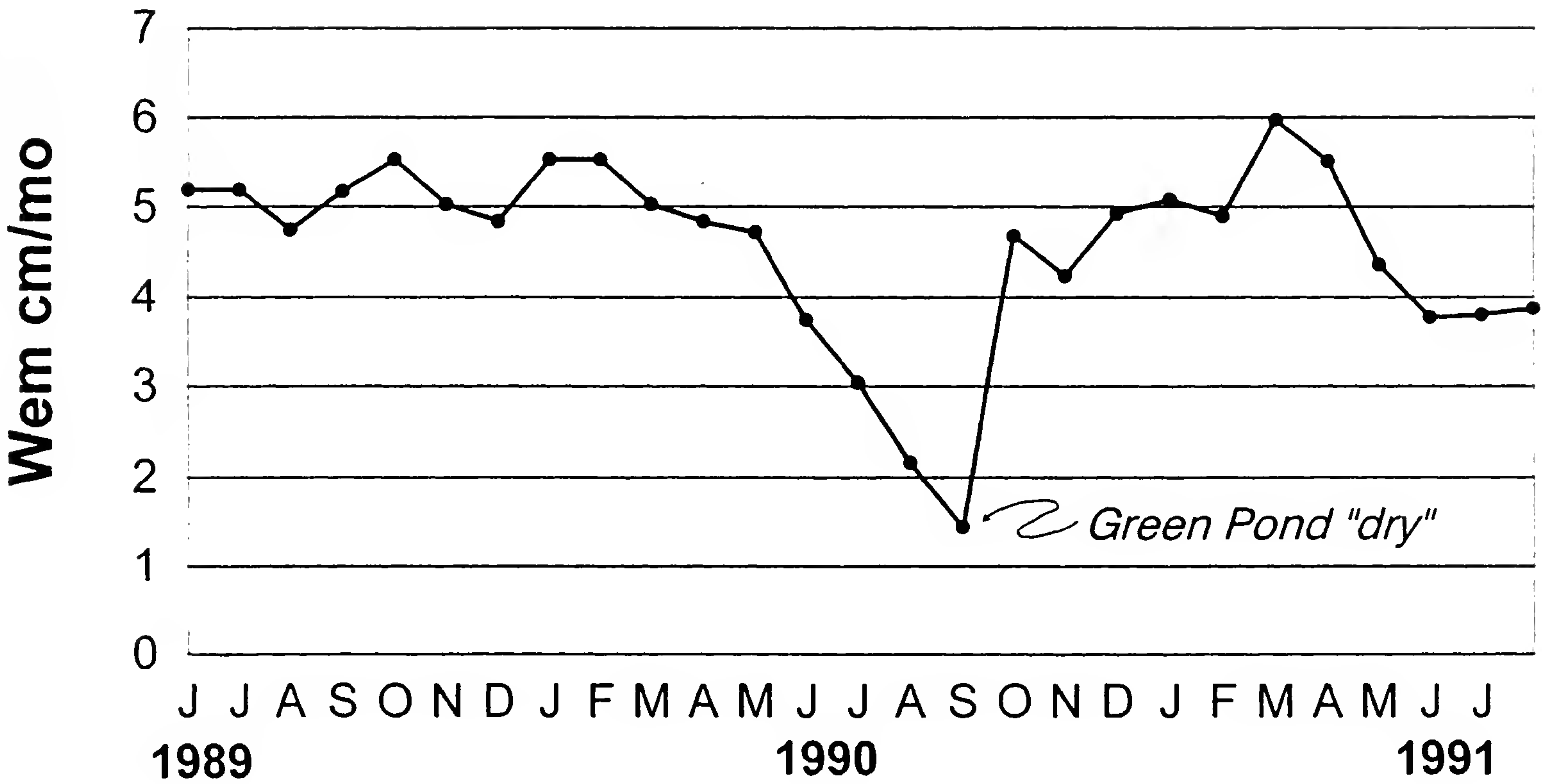

Fig. 6. Plot of Effective Monthly Recharge (W_{em}) for each month of the study period. Note that Green Pond contained no visible surface water in September 1990. W_{em} calculated using equations described in text. Recharge values for 12 months (n = 12) and a response-decay constant (D = 0.90) were used.

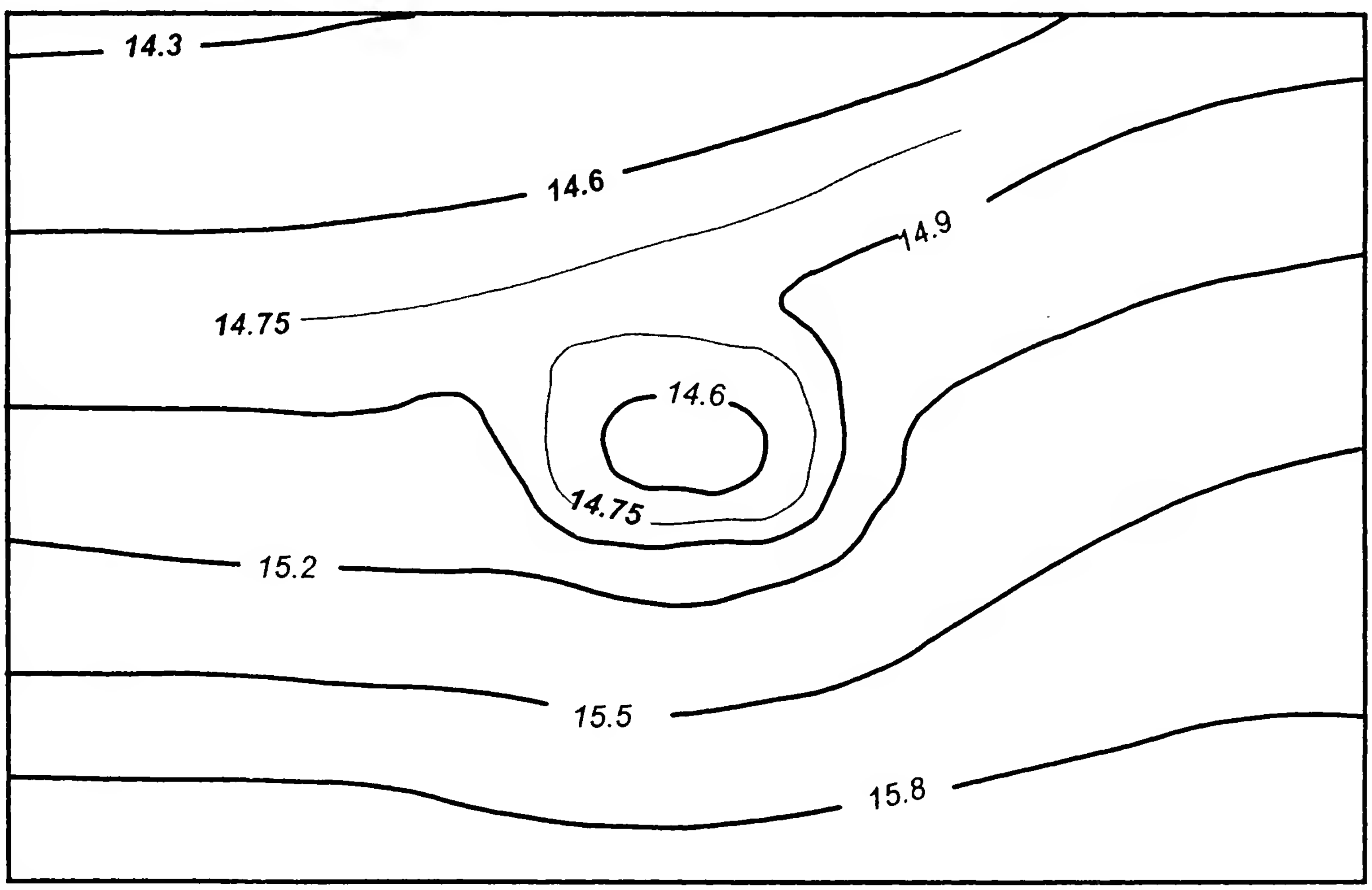

Fig. 7. Map showing distribution of heads predicted by the groundwater flow model for the Green Pond area for October 1990. Compare with Fig. 3.

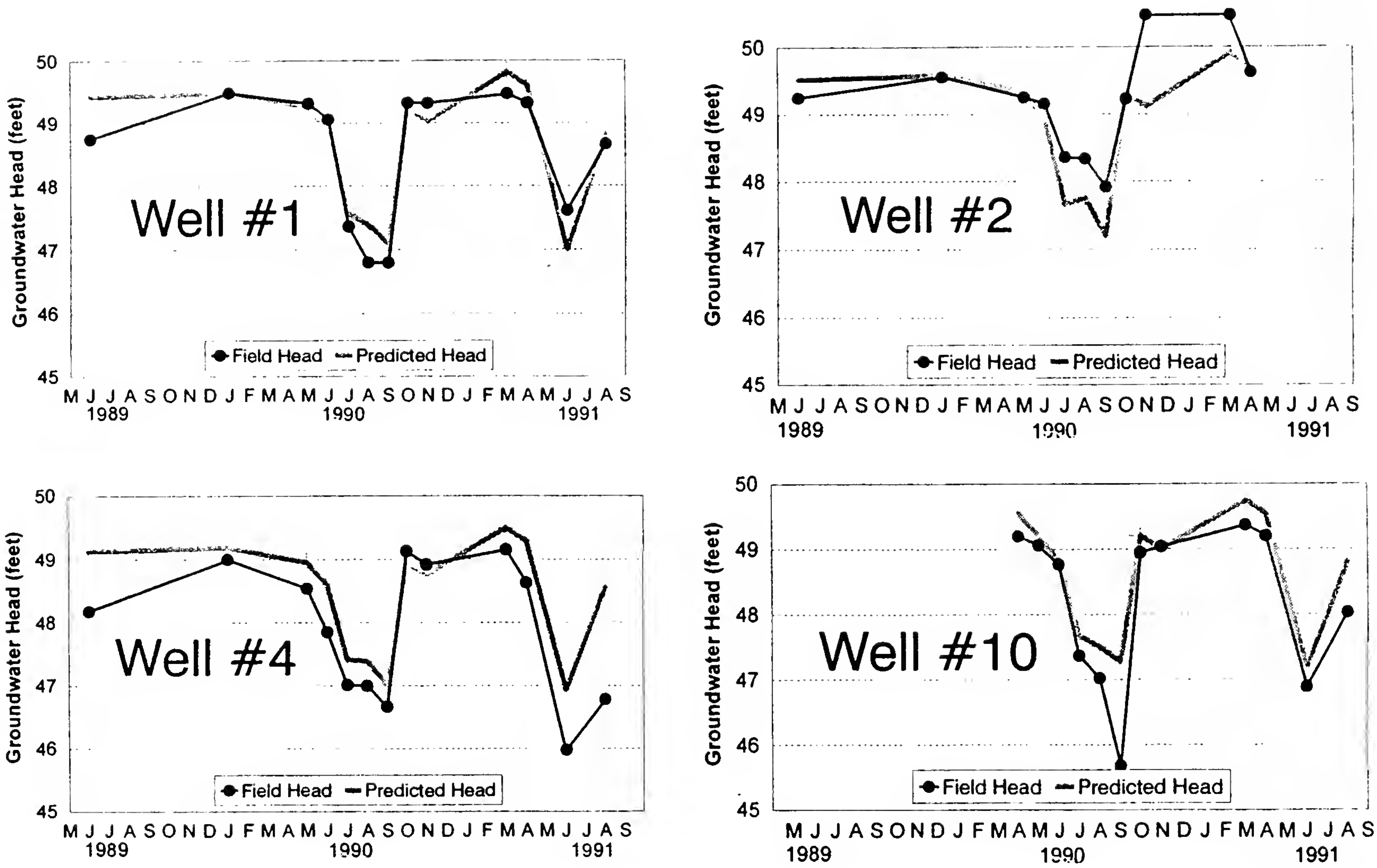

Fig. 8. Final calibration charts for results of finite difference groundwater flow model. Heads predicted by model are compared with measurements in observation wells 1, 2, 4, and 10.

error margin pre-established by the modeler (Wang & Anderson, 1982; Anderson & Woessner, 1992).

We discretized the study area into a 17x18 grid with 90-foot spacing between nodes (Fig. 5). The six cells that represent Green Pond lie at the center of the grid. The constant head boundary set along the northern boundary represents an inexhaustible supply of water located far enough from the pond to prevent interference with the pond fluctuations. No-flow boundaries along the other sides of the grid establish flow lines parallel to those margins in the areas away from the lake. These boundary condition replicate the field hydrologic setting caused by a drainage divide positioned on a low ridge more than 100 m south of the pond and the broad expanse of the plateau summit.

For hydraulic conductivity (K), our initial estimates (e.g. 100 gpd/ft^2) came from particle size analyses of soil samples at six sites around Green Pond and equations that relate mean grain size and sorting to hydraulic conductivity (Masch & Denny, 1966). The estimated value used for aquifer thickness (b = 1.5 m) in all cells came from our observations and soil survey data; we subtracted this value from the surface elevation taken from our detailed contour map (Fig. 2) to obtain the elevation of the aquifer bottom in each cell. The specific yield of unconsolidated sands, an estimate of storage (S), can range from 0.1 to 0.3 (Fetter, 1980); the best value of this parameter (S = 0.3) was obtained via trial and error.

We assigned a recharge value to each cell not in the pond by using precipitation records from Montebello, Virginia and temperature records from Big Meadows, Virginia, the closest sources of data from similar elevations. The equation used for recharge:

$$W_{mo} = P_{mo} - (P_{mo} \times I_{mo}) - Et_{mo}$$

where P_{mo} is the monthly precipitation rate, I_{mo} is the interception factor based upon the vegetation present, and ET_{mo} is the evapotranspiration calculated using the Thornthwaite (1957) method based on air temperatures. Interception values for each month (0% for May-September; 20% for October-April) represent the

reduction of rainfall due to evaporation off of the mix of hardwoods and conifers present in the area (Helvey, 1971).

Whittecar & Emry (1992) demonstrated the usefulness of the "effective monthly recharge" (W_{em}), calculated by this formula:

$$W_{em} = W_s / d$$

where

$$W_s = \sum_{a=1}^{n} (W_{mo} \times D^{a-1}) \quad \text{, and}$$

$$d = \sum_{b=1}^{n} D^{b-1}$$

where a and b are equal to the number of months prior to the month for which W_{em} is being calculated; and n is the number of months used in the calculation. D is a response-constant decay factor, usually between 0.90 and 0.99, that reflects the rate of reduction of water levels in the system; d is a normalizing factor (also see Linsley & Kohler, 1951). Fig. 6 shows W_{em} values for the months of this study.

With this capability to time-average recharge values, we ran the model in a steady-state mode for eight steps that covered 250 days, an arbitrarily large time chosen to assure convergence of solutions. Typically differences in head values calculated between successive iterations reduced to nearly zero within the first several time steps. The first step of calibration attempted to adjust the input parameters into the model so that the spatial distribution of predicted heads resembled the pattern of heads measured in the field. Heads gathered on 14 October 1990 reflect a relatively high water table and thus provided target values. The best comparison of spatial distribution came after raising the hydraulic conductivity value to 1,500 gpd/ft2. The success of this adjustment suggests

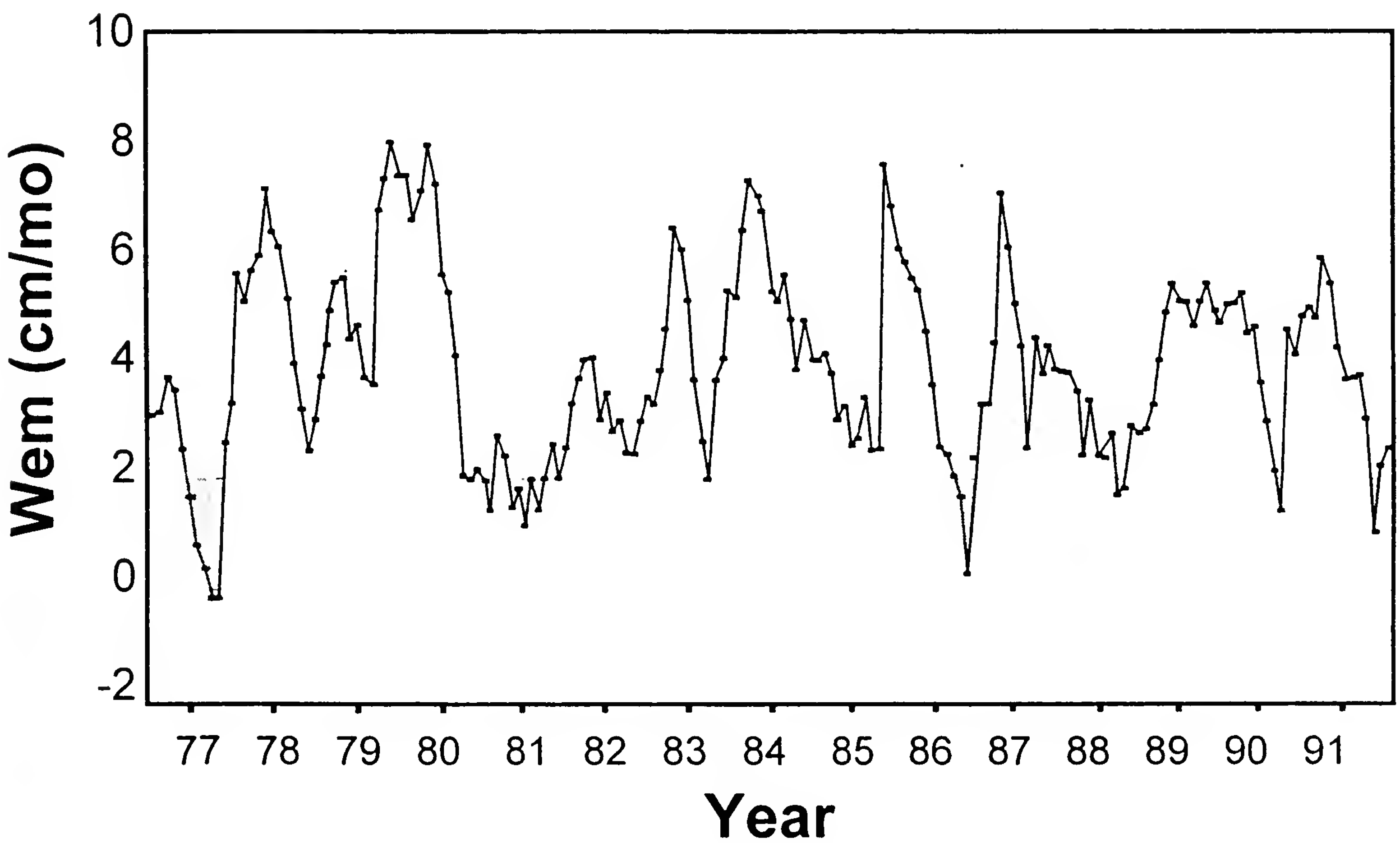

Fig. 9. Plot of Effective Monthly Recharge (W_{em}) for all months between 1977 and 1991. W_{em} calculated using equations described in text. A response-decay factor (D = 0.90) and 12 months of temperature and precipitation data from neighboring high elevation recording stations were used to calculate each W_{em} value. The shaded areas indicate the time periods that Green Pond would have been expected to go "dry," those with W_{em} less than 2 cm/mo.

that most groundwater moves through the higher permeability zones close to the base of the sandy soil profiles (Fig. 4).

The second step of calibration involved running the model for every month when we measured field heads (May 1989 through September 1991), using the effective monthly recharge values calculated with the preceding months of recharge. Measured heads in four wells near Green Pond (OW1, OW2, OW4, OW10) provided target values for each month's model prediction (Fig. 8). Use of different sets of effective monthly recharge values, calculated using different numbers of preceding months, suggest that 12 months of data ($n = 12$) and a response-decay constant (D) of 0.90 provided a reasonable match of predicted and measured heads. The largest consistent discrepancies of prediction occurred within the pond clearing and the surrounding forest during summer months, apparently indicating that actual evaporation exceeded the evapotranspiration calculated with the Thornthwaite equations. In their earlier study, Whittecar & Emry (1992) also noted an underestimation of evaporation during the summers. We compensated for this difference by increasing the losses from cells in the pond area by 0.2 gpd/ft2 during the summer months (June, July, August).

CONCLUSIONS

The groundwater head data gathered for this study (e.g., Fig. 3) indicate that Green Pond water levels reflect moderately rapid groundwater discharge from the surrounding wetland and surficial aquifer throughout most of the year. The results of the water budget analyses suggest that the shallow loamy sand soils and the small drainage area around Green Pond would be expected to pass water from a recharge event over a scale of one year or less. The gravelly zone at the base of the sandy regolith soils on Big Levels plateau may have higher conductivity than the overlying loamy sand that would contribute to the response of the Green Pond basin. For comparison, an analysis of pond levels in a basin on a thick, sandy barrier island aquifer needed 1.5 to 2 years of recharge data to calculate a usable effective monthly recharge value (Whittecar & Emry, 1992).

The usefulness of the W_{em} calculations lies in using long term records of precipitation and temperature to estimate the frequency of pond drying droughts, those that might place the greatest stresses upon aquatic species. During our study, Green Pond virtually disappeared during the summer of 1991, a time when the calculated W_{em} dropped below 2 cm/mo. Fig. 9 shows the W_{em} for all months from 1977 to 1991, as calculated from weather records kept at Montebello, Virginia. During that period, W_{em} values dropped below 2 cm/mo in six summers, usually for only a month or two but once for a period of 5 months. These data suggest that species thriving in Green Pond must have adapted to an episodic fluctuation of water levels that can dessicate the pond every few years.

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Quaternary Erosional History of the St. Marys River, Western Virginia

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INTRODUCTION

As the rivers of the central and southern Appalachian Mountains encounter rocks of varying resistance or as they compete with rivers of the Gulf drainage, the outline of drainage basins changes through divide migration and capture (e.g., Davis, 1889; Thompson, 1939). Divide shifting is particularly true where master streams in competing basins have different slopes. Erosion is favored in the steeper basin and the divide shifts gradually - occasionally abruptly - into the more gentle basin. At the headwaters of the James and Potomac River basins where the uppermost tributaries of the Maury and Shenandoah River basins compete for the available runoff, the steeper streams of the James basin ARE gaining ground at the expense of those in the southern portion of the Shenandoah basin.

The Shenandoah and its headwater streams (Fig. 1) near Greenville (Poor Creek and Pine Run) are the erosional base for large alluvial valleys and alluvial fans that emanate from the Big Levels highlands underlain by Antietam quartzite (Whittecar & Duffy, 1992). Below its headwaters near Greenville, the South River (tributary to the South Fork of the Shenandoah) flows northeast primarily on carbonate rocks with a slope of 3 m/km. It is characterized by a wide floodplain and low valley walls. On the other side of the divide and flowing southwest on the same rock types, the other South River (tributary to the Maury, then James) is a steep (8 m/km), gravel-bed stream. The east side of the river is flanked by precipitous waterfalls cascading from the Shenandoah Valley upland into a deep and comparatively narrow valley. On the Blue Ridge side of the South River lie steep tributaries below dissected remnants of fans or pediments that grade out to the level of the Shenandoah Valley uplands. The difference in headwater gradient between these two basins generates an inequity in the rate of erosion. Greater erosion allows streams tributary to the James to capture streams from the Potomac basin.

The reasons for the differences in overall basin slope and base level are largely speculative at this time but they are likely related to the length of time since different transverse streams pierced the Blue Ridge and began incising the weaker rocks of the Valley and Ridge. The James basin, presumably, pierced the divide more recently and is expanding at the expense of the previously established Shenandoah basin. We believe that St. Marys River recently—in geologic time—was diverted from the Potomac basin into the James basin because the latter is steeper and has been incising faster in the late Pleistocene (Harbor, 1996). Our study sought to document this supposition and constrain the age of the river capture event.

Sequence of Events

Given the topographic setting near the St. Marys River, inevitable northeast migration of the drainage divide resulted in diversion of streams flowing northwest off the Blue Ridge. It appears that the headwaters of the current St. Marys River fed one of the headwater streams for the Shenandoah River basin. This river flowed out of the current gap in the ridge formed by the Antietam Quartzite at a level of about 640 m (2100 ft), flowed down an alluvial fan surface like those just north of the current St. Marys River, and turned north along the path currently occupied by Pine Run downstream of the current watershed divide near Lofton, Virginia. We refer to this river as the "Lofton River." It may have been joined there, or farther upstream, by other streams the rise in the Blue Ridge. Faster incision by the South River allowed a tributary to cut headward into the fan or along the fan perimeter and capture the "Lofton River". The capture may have taken place in the shale bedrock somewhere

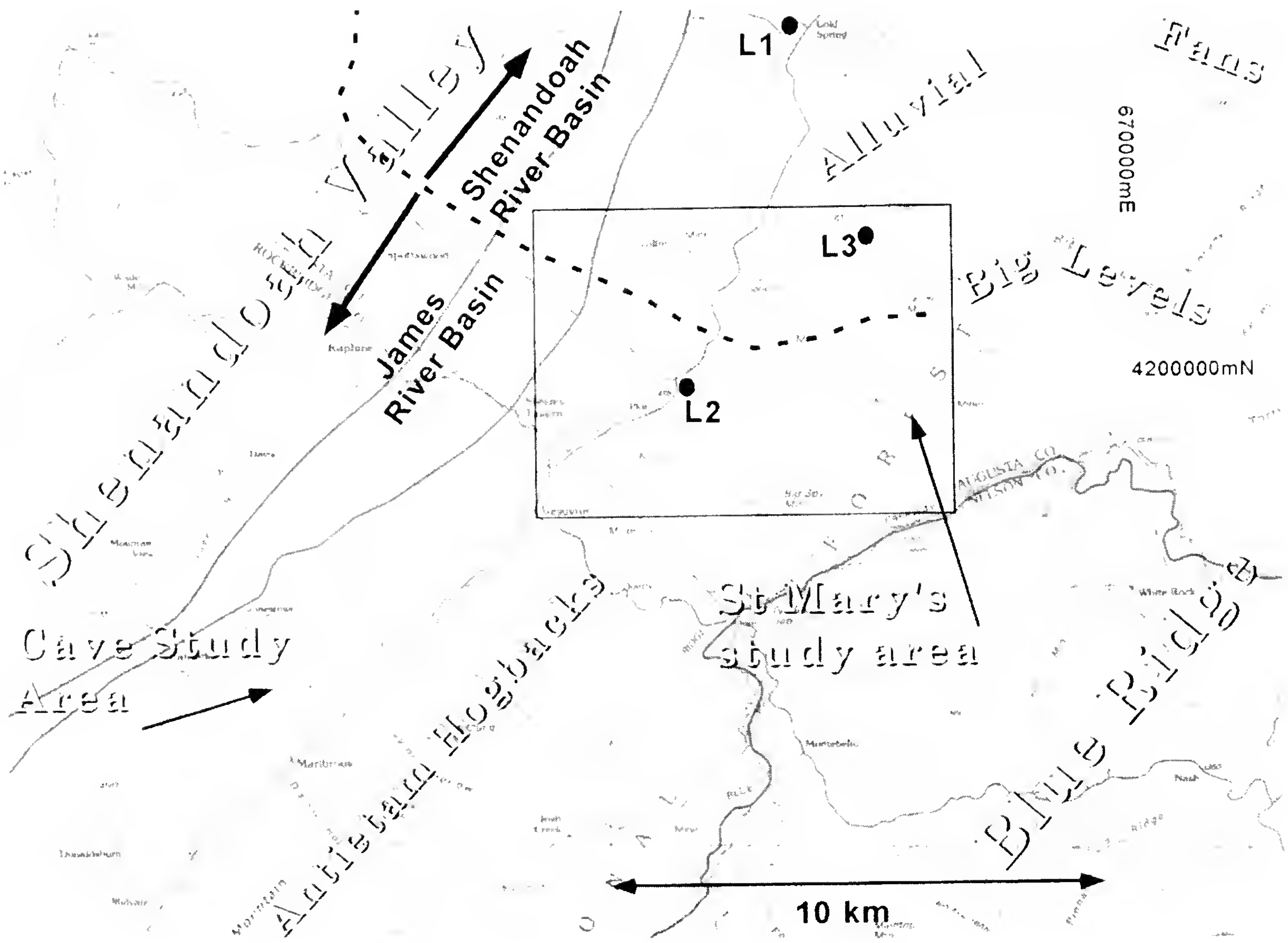

Fig. 1. Location map showing the general topography of the study area and prominent geographic features. Sample locations for sand grain lithology are indicated by L's.

downstream of State Route 608. With increased slope, and perhaps with the creation of an oversteepened reach or "knickpoint," incision migrated upstream into the headwaters area. Since capture, gully and hillslope erosion have removed most of the evidence for the "Lofton River" point of capture. The St. Marys River continues to incise at a rate greater than the streams of the Shenandoah basin.

MATERIALS AND METHODS

We used four approaches to constrain the setting and timing of this event. Geomorphic mapping, including soil and lithologic information, defined the extent and depositional nature of surficial deposits. We used the mineralogical signature and cobble orientation from soil excavations to determine ancient flow direction. Detailed soil information was used to constrain the ages of deposits. The history of the South River, which is responsible for incision of the St. Marys, was illustrated using GIS approximation of stream incision and a reconnaissance study of cave morphology along the South River.

To understand the relationship of the present drainage pattern to possible past arrangements, we evaluated topography in the Shenandoah Valley using digital elevation models with a 30 m grid spacing. Our assumption was that if rapid incision in the Maury River basin is generating basin capture at the margins, then we should be able to identify differences in incision by modeling an "upland" into which the Maury basin is more deeply incised than neighboring basins. A GIS was developed that

would search for the higher parts of a low-relief surface by locating interstream divides. Criteria used in the search were that these low-relief areas had no more than 0.18 km2 of drainage above them, were higher than roughly 67% of the surrounding elevations, and were more than 200 m from streams. These steps were necessary to exclude flat areas on floodplains near the major streams.

A model surface was fit to a sampling of these surface remnants, smoothed by low-pass filling (Fig. 2). Subtracting modern topography from this surface yields the amount of incision. The South River has achieved the greatest incision in the southern Shenandoah Valley, in part because of the weak rocks that underlie much of the very narrow river valley, but also because the river appears to have incised across the former drainage basin boundary. This former divide is seen as several highpoints on the model upland southwest of its current divide position (Fig. 2). Incision of the Maury triggered incision of the South River, which expanded to the northeast following a belt of weak shale northwest of the Blue Ridge. It appears to have captured all of the current drainage that is northeast of Big Marys Creek—possibly all drainage northeast of Irish Creek—since the time when the Shenandoah Valley upland was the local base level of erosion.

RESULTS

Initial study of the Vesuvius and Big Levels quadrangles revealed the basic topography of the study area to be a large alluvial fan projecting out from the gap in the Antietam quartzite where the St. Marys River emerged, with the southern half cut away. Instead, a new fan is being formed roughly 70 m below the old. Mapping of alluvial deposits in the St. Marys River watershed above Vesuvius, including the divide area immediately north of

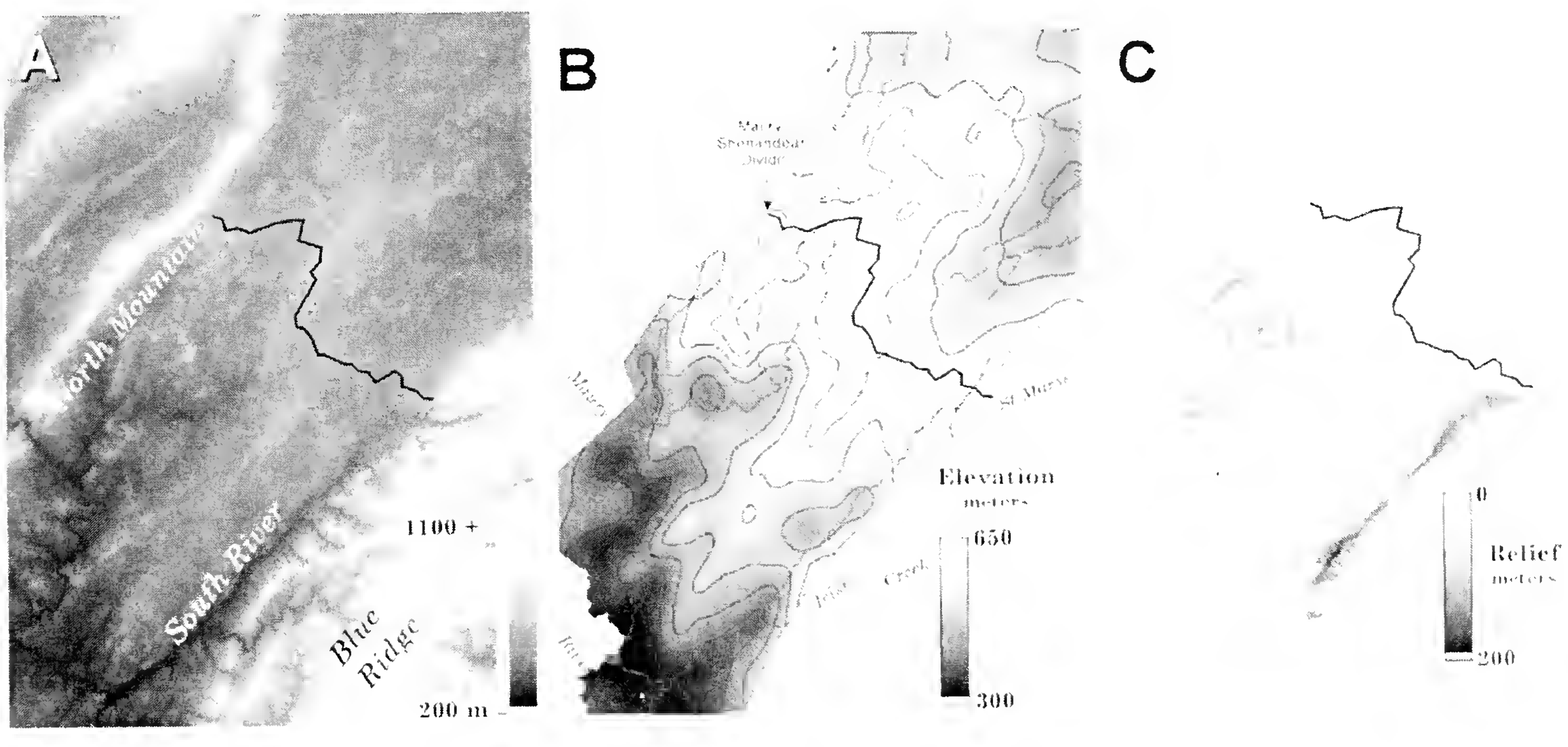

Fig. 2. Maps of the southern Shenandoah Valley showing A) a 30-m spacing digital elevation model, B) the elevation of a model surface created from interfluve remnants that might once have been part of a lower-relief Shenandoah Valley surface, and C) depth of incision below this surface, created by subtracting modern topography (A) from the model upland (B). Notice the great depth of incision for streams within the Maury basin and the generally minimal incision in the northeastern, Shenandoah/Potomac portion of the map.

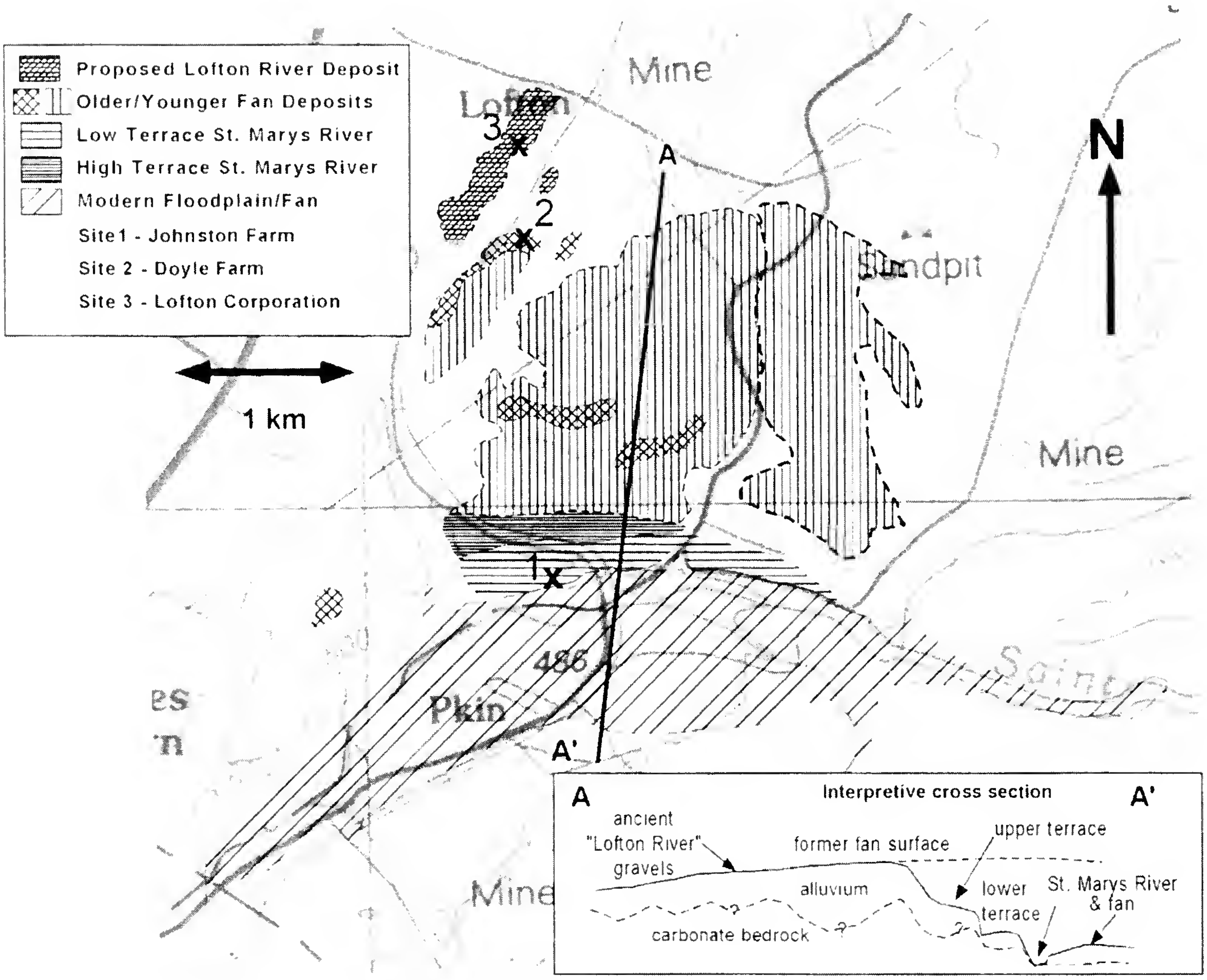

Fig. 3. Geomorphic map compiled from the Augusta Soil Survey and reconnaissance mapping. Site locations (S1, etc) discussed in text.

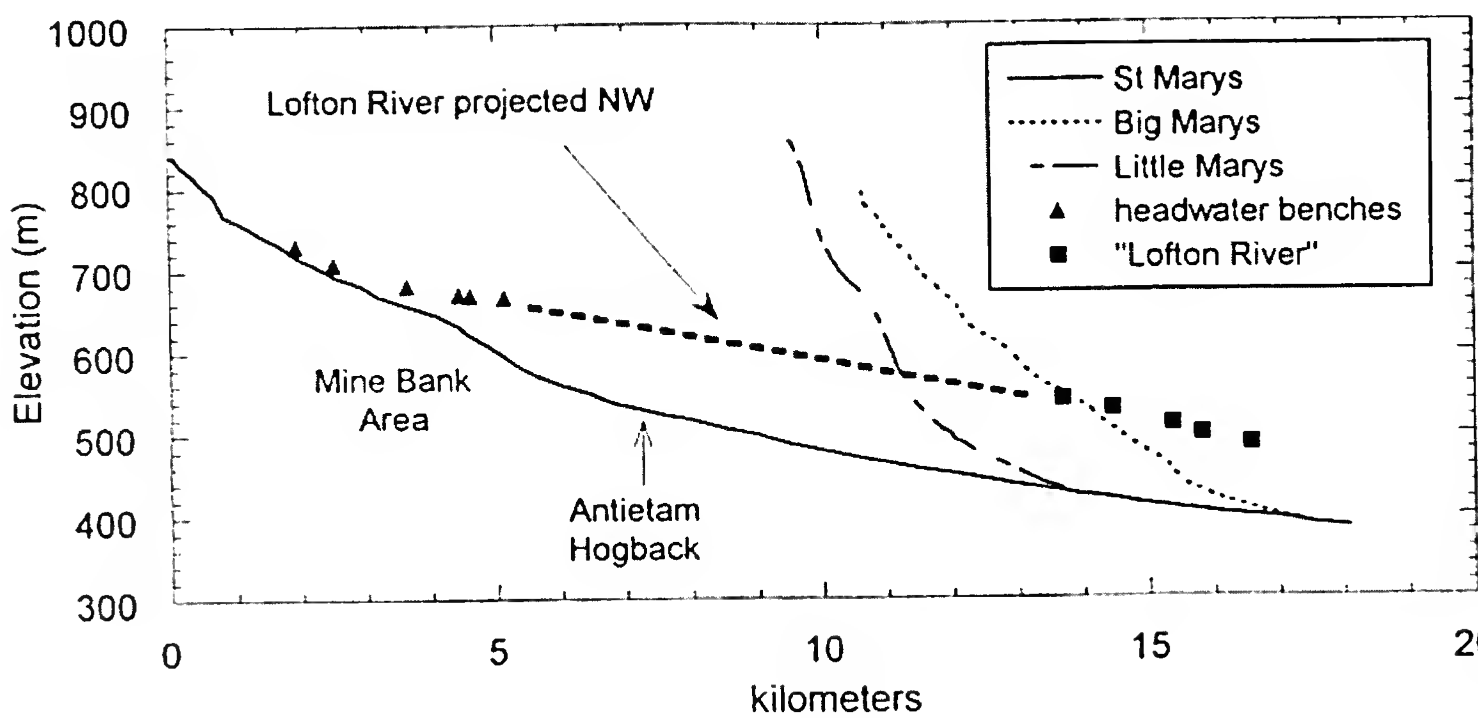

Fig. 4. Profile of St. Marys and "Lofton" Rivers. The "Lofton River" profile is made by following St. Marys River to the Antietam outcrop and then turning gently to the north to follow Pine Run along the base of the modern alluvial fans.

the river along the southernmost flank of the large alluvial fans and the area near Lofton, revealed a broad apron of alluvial material derived largely from Antietam Quarzite. These materials were generally found to underlie three landscape elements; 1) northwest-sloping, ancient fan surfaces that appear to head in the St. Marys drainage basin, 2) terraces and fans emanating from the modern St. Marys gap in the Antietam Quartzite ridge, 3) northeast-southwest trending, gently sloping terrace-like features near the toe end of the fan where it adjoins the residual carbonate terrain of the Shenandoah Valley. In addition, maps show a series of "benches" or gently-sloping terraces in the interior of the St. Marys Wilderness Area.

Soil types mapped on the Augusta County Soil Survey (Hockman et al., 1979) were used to identify the extent of former fan deposits, and using soil development as a proxy for age (e.g., Howard et al., 1993), to differentiate landforms by age (Fig. 3). An older relative age was assigned to those soils that were particularly red or clay-rich, and which possessed highly weathered cobbles of quartzite. Details concerning deposit age are covered in a following section.

Several soils indicated alluvial parent materials; Unison, Burketown, and Buchanan. All three soil types contain quartzite clasts that define the extent of the alluvial fan. The Unison soil series is found in isolated patches atop topographic peaks. The B horizon is extremely red and clay-rich, indicative of great age. Burketown and Buchanan soils also cover much of the fan. These soils are correlated with fan deposits younger than the Unison, yet they are still pre-capture. They are typically less red than the Unison. The benches within the St. Marys headwater area, as well as the slopes of the Antietam hogbacks, consist of the Monongahela series. Like the Buchanan and Burketown soils, the Monongahela soil is probably old enough to predate capture; they are merely colluvial instead of alluvial. The youngest soils of the fan, other than those in the floodplain, appear to be those of the Sherando series. This soil covers the St. Marys River terrace near Site 1 (Fig. 3). Its color does not redden significantly. Other soils developed in residuum of bedrock denote areas away from the fan or where the fan material has been completely eroded. It also became evident that younger soils covered the older Unison soils in many places. Three backhoe pits approximately 2.5 m in depth were dug to examine the soils and alluvial materials at key locations. The pits at Sites 2 and 3 probably both consist of the younger soils developed in material deposited on materials hosting the older Unison soil. This appears to be the case even on the St. Marys River terrace (site 1). Multiple layers of alluvium are common in a fan environment (Whittecar & Duffy, 1992).

The southern half of the Lofton River fan has been cut away. However, isolated peaks of alluvial soils similar to the fan soils were noted to the west of the river on the edge of the upland (Fig. 3). These deposits contained quartzite cobbles and are mapped as the same soil series as much of the old alluvial fan to the north. These areas are interpreted to be the remnants of the fan prior to the incision of the St. Marys/South River system. We have found alluvial deposits west of the river in just one other location along the South River.

A key aid in determining relative ages of fan soils was the degree of weathering of quartzite clasts. Because these cobbles weather as a function of time, a relative age can be assigned based on the degree of weathering (Whittecar & Duffy, 1992). Quartzite cobbles near the bottom of the pit at Site 3, which is part of the old fan, could be sliced with a knife, indicating a very great age. Higher in the B horizon, quartzite clasts appeared much younger. This arrangement supports the idea of a composite or buried soil profile.

Lofton River

Topographic form near the present-day drainage divide suggests a relict fluvial environment. Site 3 sits atop a long, linear ridge trending northeast. Reconnaissance soil pits dug in the ridge revealed a poorly developed A horizon overlying a thick (30 cm) layer of silt, presumably windblown loess. This E horizon is underlain by a brown B horizon containing quartzite clasts. This stratigraphy suggests an alluvial origin, where floodplain silts are laid atop channel gravels/cobbles, and implies that the ridge is a wide floodplain or terrace without a nearby river. The ridge merges with a terrace of Pine Run just 5 km downstream (northeast).

The "Lofton River" flowed in a valley, the margins of which exist today as the high benches containing iron and manganese ores in the Mine Bank area (Stose et al., 1919) and out onto the fan surface. The slope of the "Lofton River" was probably similar to the current slope of Pine Run, although the latter is slightly incised. We can project the elevation of Pine Run and the deposits found near Lofton up into the St. Marys headwaters (Fig. 4). Here we found iron and manganese deposits that are formed by deep weathering and leaching of limestone saprolite, usually protected by an alluvial or colluvial capping. This process suggests great age and supports the existence of a relatively stable, older land surface now abandoned.

The keystone of our hypothesis is the assumption that the St. Marys River once flowed north to the South Fork of the Shenandoah River. Two types of evidence confirm this flow direction. First, the directions of cobble imbrication near Lofton suggest flow to the northwest (Fig. 5). Cobbles transported by running water typically come to

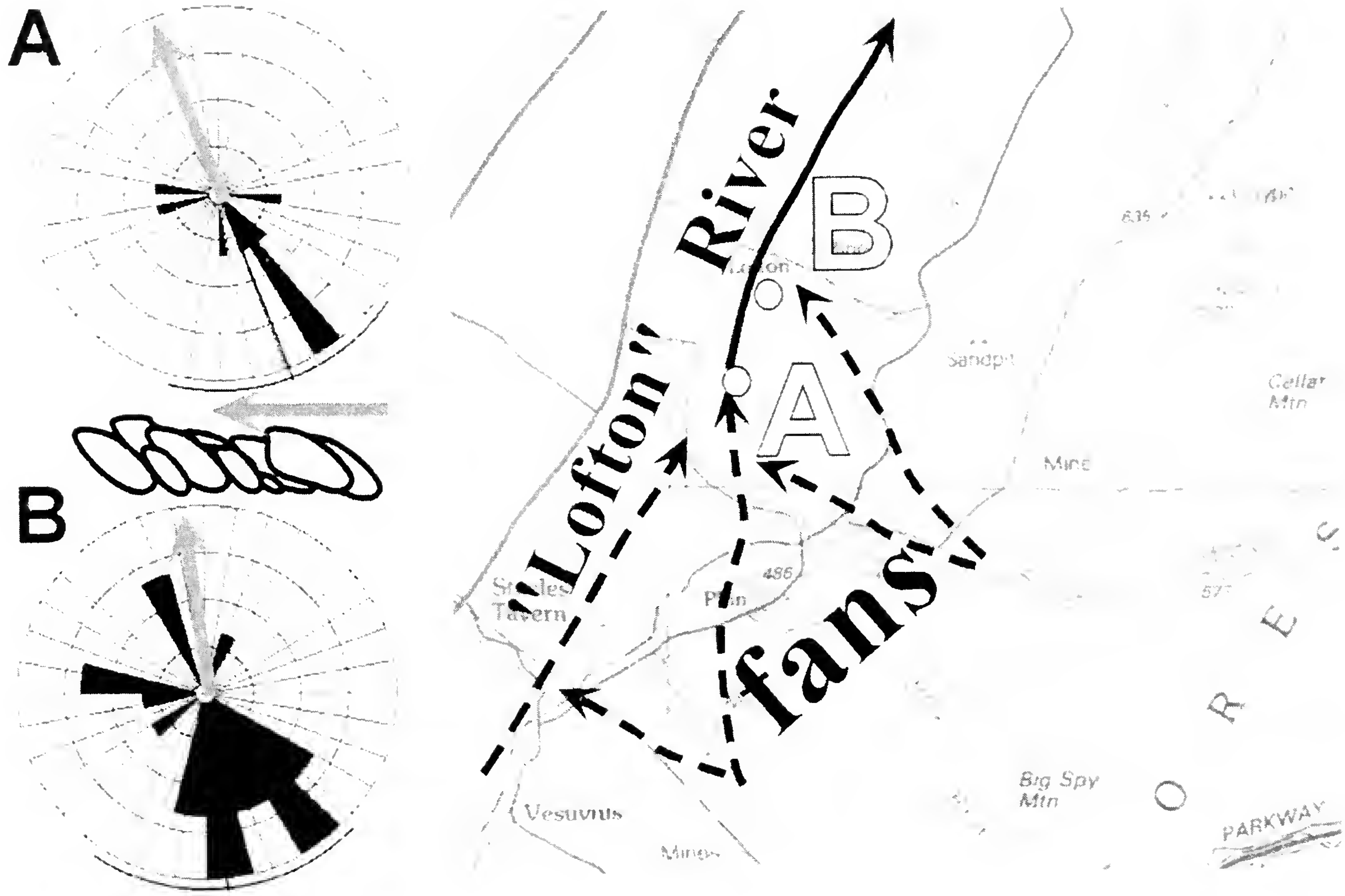

Fig. 5. Cobble imbrication cobbles in two study pits. The rose diagrams on the left give the dip direction of the cobble, and the grey arrow is drawn along the mean to show flow direction.

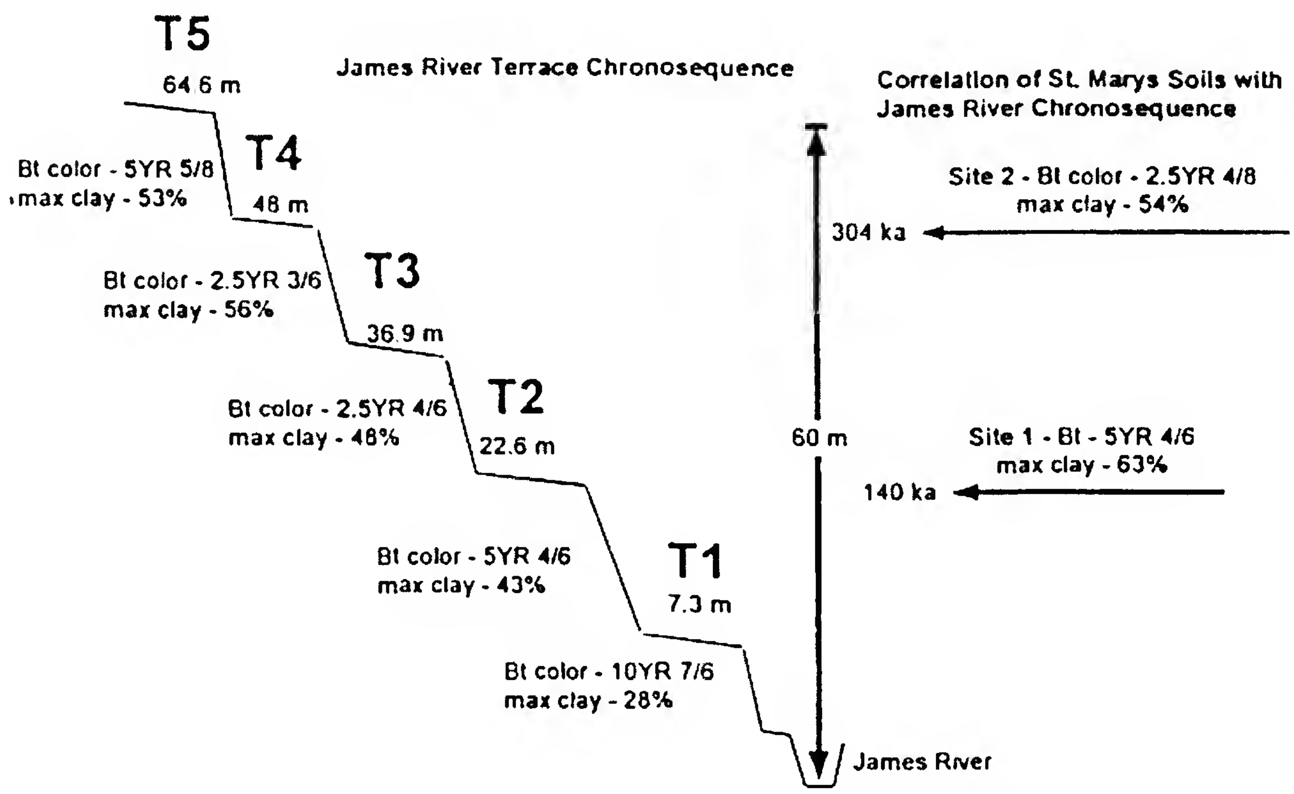

Fig. 6. Comparison of the study area soils to a sequence of soils on the James River near Gala, Virginia (Elliott, 1998). The ages of the James River terraces and the correlative soils in the study area are estimated using the cosmogenic isotope age of a 57 m terrace near Iron Gate, Virginia.

rest with their long axes perpendicular to flow and the largest flat side dipping upstream. Dip direction can vary significantly, but should define a 180-degree arc centered on the upstream direction. We measured the dip direction of between twelve and twenty cobbles in the trenches. All measurements were from cobbles in the lowest 1 m of the pit to avoid problems with disturbances from frost and biological overturning. The soils were Unison, indicating great age. In both cases, data indicate a dip to the southeast, which implies northwest flow. This is consistent with the flow direction of a stream running down or along the toe of the alluvial fan.

The flow direction of the "Lofton River" toward the northeast is also suggested by differences in the mineralogy of the sand grains taken from the ancient river course and its potential headwater areas. The "Lofton River" sample was taken from a more northeastern equivalent of the Lofton terrace exposed at a roadcut along Pine Run east of Greenville ("L1" Fig. 1). Samples from the floodplain of St. Marys River downstream of Spy Run (L2) and along Cold Spring Branch (L3) where it leaves the Antietam highlands constrain the potential source of material that could have been transported out to the "Lofton River" location. The Cold Spring and St. Marys samples differ in mineralogy; only the St. Marys sample contains mineral grains associated with crystalline basement rocks. The St. Marys alluvium contains abundant ilmenite and some rutile, whereas Cold Spring Branch samples contain no ilmenite and no rutile. The "Lofton River" sample has common ilmenite and few rutile. The latter sample is likely to have been changed by great weathering, but still suggests that one source for the sediment was the St. Marys headwaters. The source for the igneous minerals is the Pedlar Formation which formed the core of the Blue Ridge in the study area. None of the mountain streams in the area immediately north of the St. Marys River has headwaters underlain by the Pedlar formation. Of course, other streams to the southwest with basins underlain by crystalline basement southwest of the St. Marys River may also have been part of the headwaters.

Timing

We constrain the age of the capture event by comparing soils in the study area to soils developed in a series of five James River terraces on Devonian shale near the town of Eagle Rock (Elliott, 1998). This soil chronosequence demonstrates increasing soil thickness, soil redness, and B-horizon clay percentage with height above the river. The age of this terrace sequence is itself constrained by cosmogenic isotope dating of quartz pebbles obtained from an abandoned meander 57 m above the James River near Iron Gate, which is approximately 15 km upstream. This date returns an incision rate of 160(40 m/million years (Erickson, 1998), which we use along with the terrace elevation to determine age. The 60 m terrace correlates well between these two sites along the James River, but we are forced to assume a constant incision rate to determine soil ages at the downstream site. To correlate the James River terrace soils to the St. Marys field area, we rely mainly on the color (Munsell standard notation) and maximum clay percentage in the red, clay-rich B horizon (Fig. 6).

The younger fan remnants and alluvium in the Lofton soil pit (Site 3) give the youngest age for deposits of the Lofton River while the St. Marys River terrace (Site 1) is the oldest deposit post-dating the capture event (Fig. 2). The upper soil profile at Site 2 and the soil at Site 3 match with terraces at or above 48 m along the James. The James River incision rate yields an age of approximately 300,000 years. Site 1 corresponds most closely with the 22.6 m terrace from the James River chronosequence. The color of the clay-rich Bt horizon in both of these terraces match; however, the maximum clay percentage of the Bt horizon was about 50% greater in the Johnston Farm soil than in the James River terrace soil (Fig. 6). The source of increased clay may be in the easily weathered crystalline rocks of the St. Marys River, which are not found in the James River Basin, or in a depositional mechanism that carries more clay-rich sediment, such as a debris flow. Given this caveat, the Site 1 soil was assigned an age of approximately 140,000 years. Capture of the St. Marys River by the James River basin occurred before this date.

The degree of weathering of quartzite clasts indicates that the pre-capture fan had been re-worked for some time prior to capture. According to the Whittecar & Duffy (1992) data, many of the cobbles in the trench at Sites 2 and some in Site 3 may have been deposited as early as the Tertiary. This is extremely old for a surface deposit. Cobbles nearer the top of the trench at Site 2 were not nearly as disintegrated, indicating a younger age. The degree of weathering of these cobbles was similar to those found in the 48 m terrace along the James River (Elliott, 1998). It is clear that the path of the Lofton River migrated laterally across its valley, reworking older deposits and covering them with younger layers. Site 3 appears to support the idea of a relatively young deposit (Buchanan soil) overlying a very old deposit (Unison soil). Similarly, layering of deposits and soils of various ages are found at Site 1. The St. Marys River terrace is not a flat surface; rather it is a rolling plain. The Augusta County Soil Survey (Hockman, 1979) categorizes much of the terrace as Unison, although there is clearly a thin mantle of Sherando soil overlying much of it.

The Shenandoah Valley upland west of the South

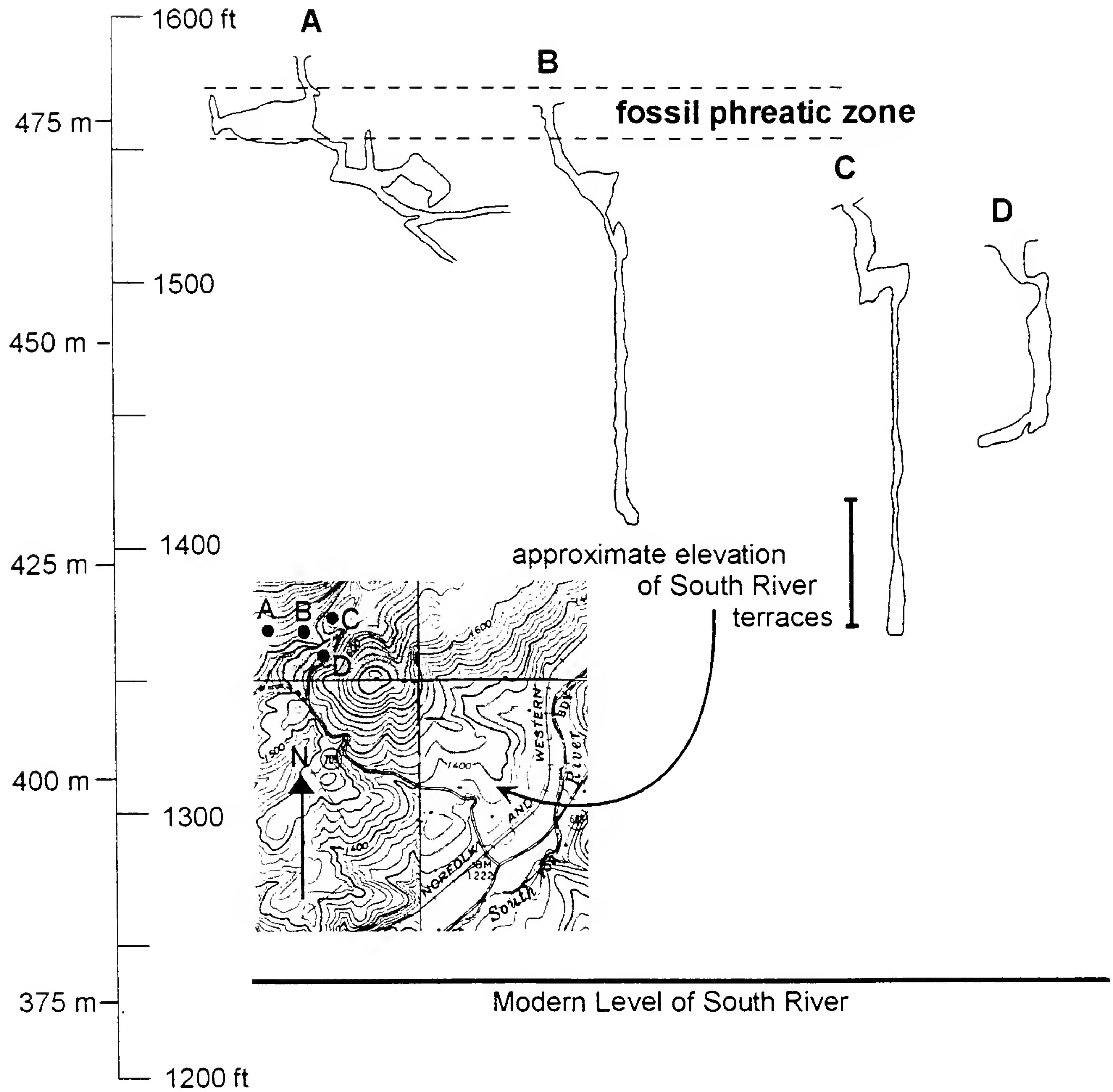

Fig. 7. Cave cross sections showing the narrow fissure shape, possible paleo-phreatic upper rooms, and a depth coincident with terraces of the South River. Cave profile and cross section height and width were measured with tape, compass, and inclinomter.

River near the confluence of Big Marys Creek contains a number of sinkholes and caves, as well as isolated occurrences of quartzite-bearing alluvium.The shape of cave passages below this surface along the South River corroborates rapid incision followed a more stable period when streams flowed farther out into the Shenandoah Valley (Fig. 7). Solution of large caverns often occurs at the elevation of the water table; thus, elliptical passages record position of a relatively stable base level. Some caves have relatively broad rooms near the surface connected by small passages to the chasms below. The elliptical shape, particularly for cave A, and size of surface rooms suggests they developed when the water table was stable and at least as high as the entrance. The water table level then dropped rapidly, allowing the deep, narrow fissures to develop along structurally-controlled

northeast-trending fractures found throughout the valley. The passages again widen at a depth as much as 40 m (130 ft) below. Room elevations at the bottom of these fissures are roughly coincident with a broad terrace along the South River at an elevation of 425 m (1,400 ft). The modern-day South River lies at 375 m (1,230 ft).

The terraces and cessation of cave incision represent the next period of stability in water table level connected to the South River. Further cave exploration may reveal broad rooms at the bottom of the fissures. In any case, another incision episode followed, lowering the South River to its present elevation.

CONCLUSIONS

The geomorphic history of the St. Marys River region is one of incision. Our evidence suggests that the region went through complex changes to reach its present form. Knickpoint migration is the most probable mechanism for the incision of the St. Marys/South River system. It is also the cause of the drainage divide migration. Cave shape and terrace morphology support the idea of at least two periods of stable local base level separated by rapid incision along the South River, leading up to the St. Marys River. The first of these incision episodes, beginning at most 300,000 years ago along the Maury River Basin, caused a shift in the flow direction of the Lofton River by giving a headwater stream of the South River enough advantage to erode headward into the Lofton drainage. A stable period followed during which many of the Lofton River fan deposits were shifted and reworked. Another incision episode followed, finishing over 100,000 years ago, forming the St. Marys River terrace on older fan deposits. Incision episodes were probably complex responses, with periods of cutting and filling and rapid channel migration across the valley. In this manner, the complex geometry of the present-day alluvial fans in the St. Marys area was developed.

ACKNOWLEDGMENTS

We are indebted to many landowners for permission to study and dig on their property; C. Kenneth Doyle, Fred and Cathy Fitzgerald, the Lofton Corporation, and "Son" and Clara Johnston. Washington and Lee University provided funding through R.E. Lee and Glenn Grants. Bob Thren showed us the caves, helped us interpret their form, and provided the cave survey drawings.

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The Acid-Base Status of the St. Marys River: the Virginia Trout Stream Sensitivity Study Results

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INTRODUCTION

The St. Marys River in Augusta County is among the most well known and well studied of the upland streams in Virginia that have been affected by deposition of acidity from the atmosphere (Webb et al.,1989a; Cosby et al., 1991; Deviney & Webb, 1993). The Virginia Department of Game and Inland Fisheries has documented dramatic biological degradation in this stream consistent with acidification effects, including loss of both benthic and fish taxa (Kauffman et al., 1999; Bugas et al., 1999). The physiographic setting of the St. Marys watershed is similar to that of other streams in the Blue Ridge mountains where acidification related changes have been observed in stream water composition and aquatic biota (Ryan et al., 1989; Eshleman et al., 1995; Bulger et al., 1995).

Information concerning the acid-base status of surface waters in the St. Marys River watershed has been obtained through the Virginia Trout Stream Sensitivity Study (VTSSS). The VTSSS was designed to provide continuing information on the acid-base status of mountain headwater streams in western Virginia that support native brook trout (*Salvelinus fontinalis*). In the spring of 1987, a synoptic survey was conducted in which stream water samples were obtained for 344, or about 80%, of the region's identified native brook trout streams. Analysis of these samples indicated that a high proportion of this biologically defined population of streams is sensitive to acidification due to atmospheric deposition (Webb et al., 1989b). Following this survey, a sample (n = 65) of this stream population was selected for long-term monitoring and research. The selection criteria included relative absence of watershed disturbance, geographic representation, and coverage of the sensitivity range associated with the stream population. The St. Marys River was among the most sensitive of the selected streams.

In this report, we provide a summary of water quality information collected for the St. Marys River watershed through the VTSSS program. We further provide an analysis of acid-base status in surface waters of the watershed. For this purpose, we focus on spatial and temporal variations in acid-neutralization capacity (ANC), a parameter which effectively indicates the balance between acids and bases in solution (Baker et al., 1990a). Surface water acidification, defined as a loss of ANC (Turner et al., 1990), occurs when concentrations of strong-acid anions (sulfate, nitrate, and chloride) increase relative to concentrations of base cations (calcium, magnesium, potassium, and sodium ions). If surface water ANC is reduced to sufficiently low values, acidity may increase, as indicated by a depression in pH, to a range associated with adverse effects on fish and other aquatic life (Baker & Christensen, 1991). Although surface water acidification involves a decrease in both ANC and pH, the relationship is nonlinear. At lower ANC levels, a given change in ANC results in more change in pH than occurs given the same change in ANC at higher ANC levels. The ANC of surface water is thus an indication of sensitivity to acidification, an indication of present acidity, and an indirect measure of surface water suitability for aquatic biota.

Watershed Description

The St. Marys River watershed is defined here as the approximately 26.9 km^2 drainage area above the VTSSS stream water sampling site designated VT41. This area is located on the western flank of the Blue Ridge Mountains in southeastern Augusta County and within the St. Marys Wilderness of the George Washington National Forest.

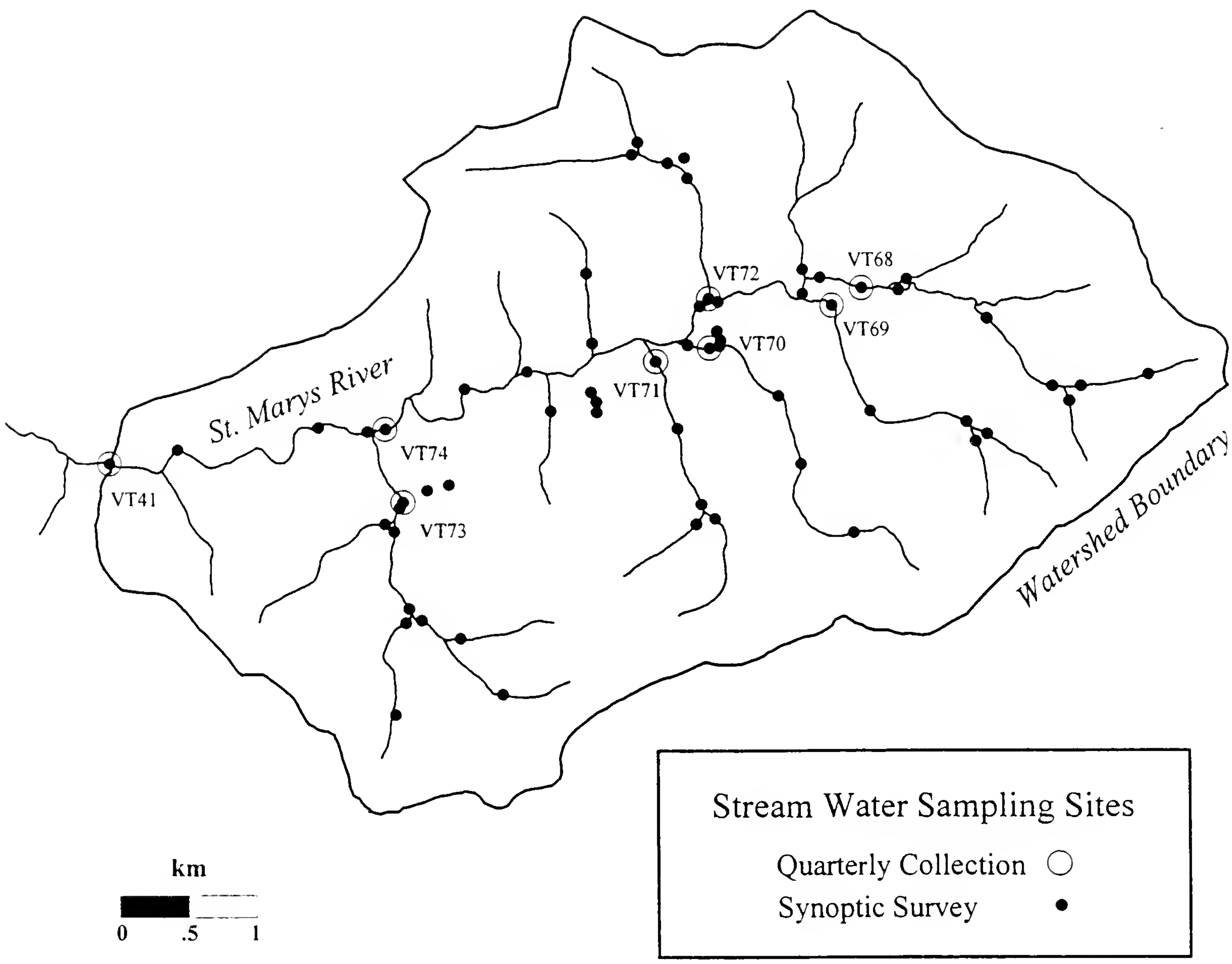

Fig. 1. VTSSS stream water sampling sites in the St. Marys River watershed.

VT41 is sited approximately 200 m upstream from the Wilderness boundary. Within the wilderness, the mainstem of the St. Marys River is approximately 9 km long, with six perennial tributaries. Approximately 3 km downstream from the wilderness boundary, the St. Marys River flows into the South River of the James River basin.

Watershed characteristics for the St. Marys River have been described by Deviney & Webb (1993). Terrain in the watershed is rocky and steep, except in some riparian areas along the mainstem. Elevations range from 530 to 1,100 m. Vegetative cover in the area is dominated by species with relatively low nutrient and moisture requirements such as chestnut oak (*Quercus prinus*), pitch pine (*Pinus rigida*), and mountain laurel (*Kalmia latifolia*). Large areas of the forest were defoliated by the larvae of the gypsy moth (*Lymantria dispar*) for several successive years during the early 1990s. The geology of the watershed has been described by Werner (1966). Most of the watershed is underlain by the primarily siliciclastic rocks of the Chilhowee Group (Antietam, Hampton, and Unicoi Formations). Small portions are underlain by residual clay deposits of the Shady Formation and by basaltic rocks of the Catoctin Formation. Evidence of previous mining and processing of manganese ore, including pits and other disturbed areas, is present at several sites on or adjacent to exposures of the Shady Formation.

Since 1984, the St. Marys River watershed has been managed as a federally designated wilderness area. In response to evident losses of aquatic biota due to acidification, the USDA Forest Service has recently initiated a project to neutralize acidity in the St. Marys

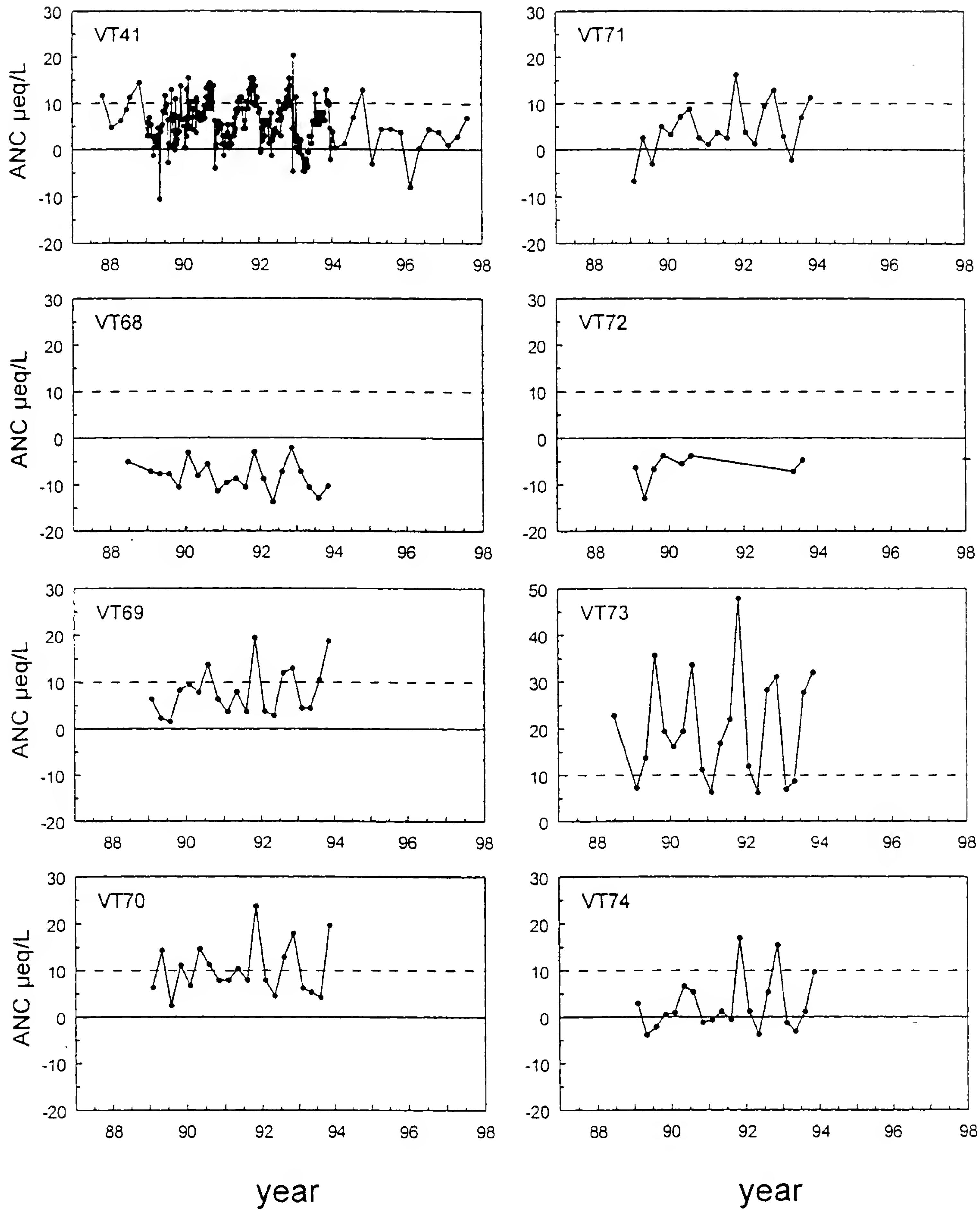

Fig. 2. ANC concentrations for VTSSS sampling sites in relation to ANC criteria for adverse biological effects associated with long term exposure (10 μeq/L) and short-term exposure (0 μeq/L).

River and the lower reaches of its major tributaries by direct application of limestone sand.

MATERIALS AND METHODS

Following the regional synoptic survey in the spring of 1987, seven sites on the mainstem and major tributaries of the St. Marys River were selected for quarterly sampling and analysis. Beginning in 1988, sampling frequency at VT41 was increased to weekly. Detailed synoptic sampling surveys were conducted in the watershed in March of 1992 (n = 62) and April of 1993 (n = 45). In 1993, sampling frequency at VT41 was reduced to quarterly and sampling at the other quarterly sites was discontinued. A map of the St. Marys River watershed indicating sample locations is provided in Fig. 1. Geographic coordinates, elevations, and catchment areas of the quarterly sites are listed in Table 1.

Procedures for sample collection included use of prewashed polyethylene bottles, multiple rinses with stream water at the sample sites prior to sample collection, and maintenance of samples in insulated containers with refrigerant during transport to the project laboratory at the University of Virginia in Charlottesville, Virginia. Analysis was conducted for major dissolved constituents by methods commonly used for acid-deposition studies (e.g., USEPA, 1987; Morrison, 1991). Instrumentation and methods specifics are indicated in Table 2. Quality

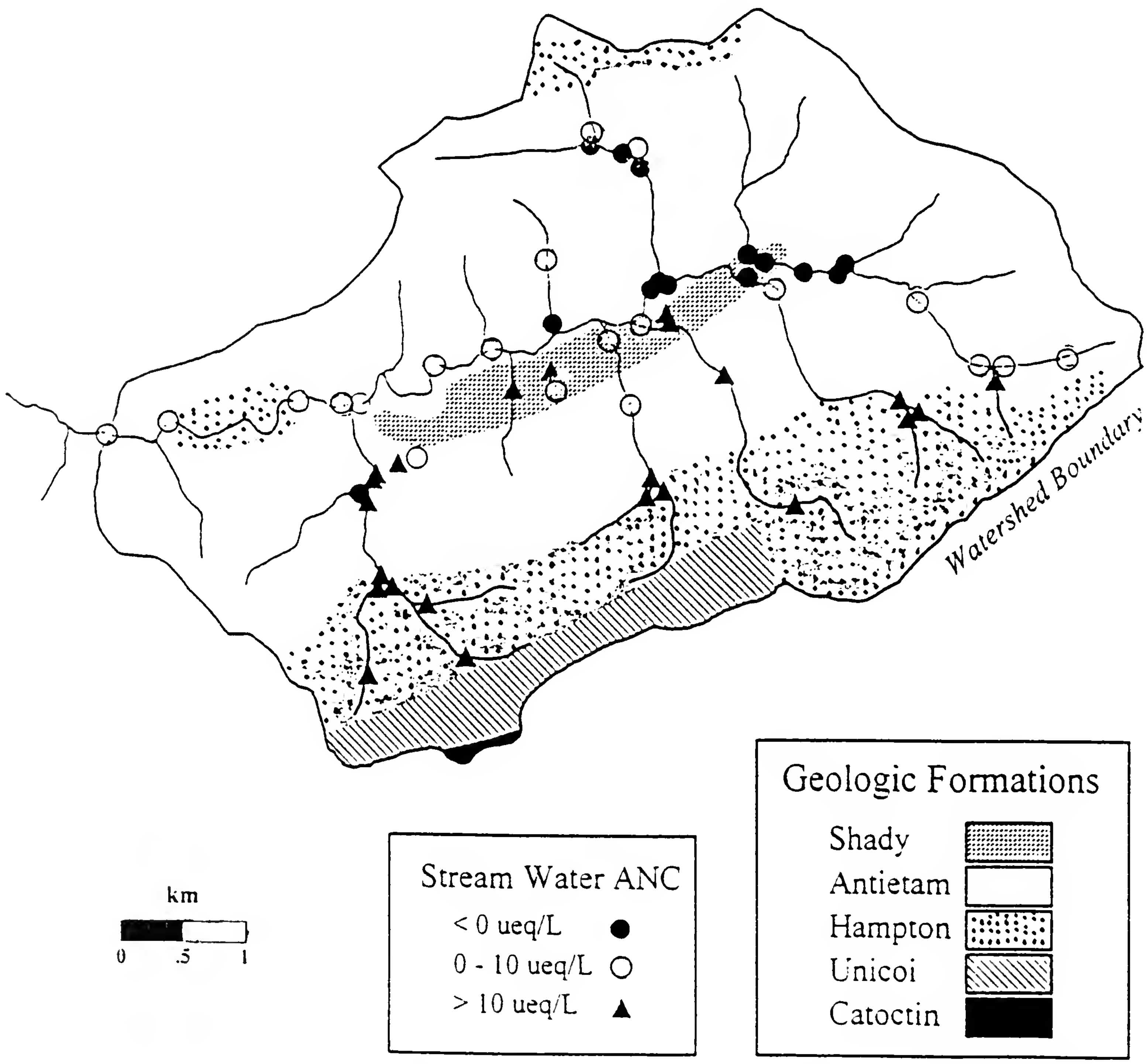

Fig. 3. ANC distribution for March 1992 synoptic stream sampling survey in St. Marys River watershed.

Table 1. VTSSS monitoring sites in the Saint Marys River watershed.

SITE	STREAM	MAPNAME	UTM-EW	UTM-NS	ELEV	AREA
VT41	ST MARYS -LOWER	VESUVIUS	663725	4198876	530	26.93
VT68	ST MARYS -UPPER	BIG LEVELS	669150	4200232	725	3.86
VT69	CHIMNEY BRANCH	BIG LEVELS	668936	4200105	725	1.99
VT70	BEAR BRANCH	BIG LEVELS	668052	4199789	677	2.14
VT71	MINE BANK CREEK	BIG LEVELS	667667	4199685	677	2.01
VT72	HOGBACK CREEK	BIG LEVELS	668039	4200139	689	2.17
VT73	SUGARTREE BRANCH	BIG LEVELS	665855	4198630	628	4.09
VT74	ST MARYS -MIDDLE	BIG LEVELS	665718	4199156	579	19.43

Notes: MAPNAME = USGS 7.5 Minute; ELEV = elevation in meters; AREA = catchment area in km^2

Table 2. Laboratory Analytical Methods.

Aliquot	Instrumentation	Method
Acid-neutralization capacity	Bechman Psi pH Meter (No. 123114); Corning Calomel Combination pH Electrode (No. 476530)	Gran titration with 100 ml sample aliquot and 0.005 N HCl titrant. Within-aliquot stability ($\leq$0.01 units/min.) obtained for endpoint determinations.
pH	Bechman Psi pH Meter (No. 123114); Corning Calomel Combination pH Electrode (No. 476530)	Potentiometric measurement with open-system samples. Within-aliquot stability ($\leq$0.01 units/min.) and sequential aliquot agreement ($\leq$0.03 units difference) obtained.
Calcium, Magnesium, Potassium, and Sodium	Thermo Jarrel Ash AA/AE Spectrophotometer Model Smith-Hieftje 22	Flame atomic absorption spectrophotometry. Li/La added to aliquot.
Sulfate, Nitrate, and Chloride	Dionex 4000I Ion Chromatograph; HPIC AS4A Separator Column; HPIC AG4A Pre-Column; AMMS Anion Micro-Membrane Suppressor	Simultaneous determination by ion chromatography. Injection volume: 200µL. Eluent: 2.2 mL 3.4-4.5 mM Na_2CO_3/minute. Regenerant: 3-4 ml 0.035 N H_2SO_4/minute.
Silica	Technicon Autoanalyzer II	Colorimetric detection by molybdate blue technique.
Aluminum, total monomeric	Technicon Autoanalyzer II	Colorimetric detection with open-system samples by pyrocatechol violet technique.

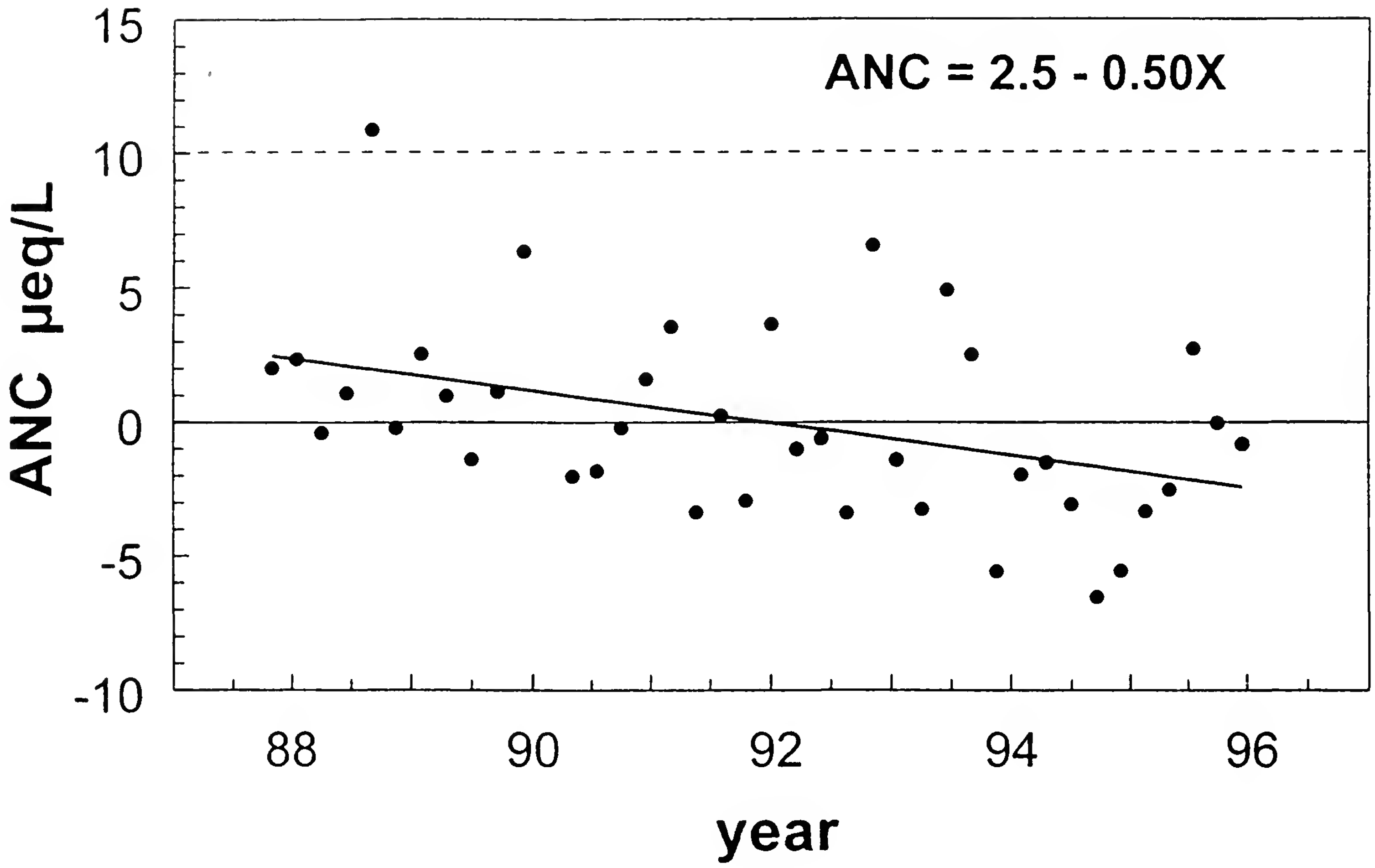

Fig. 4. Change in flow-adjusted ANC concentrations of St. Marys River (VT41) during the period of October 1987 to July 1997. The trend is significant at P<0.01.

assurance procedures included determination of charge-balance error and analysis of sample duplicates, reference samples, and field blanks.

Although most VTSSS sites, including those in the St. Marys River watershed, are not gauged for discharge, we have used discharge data from USGS stations within 80 kilometers to interpolate daily discharge for VTSSS quarterly sample sites on days that samples were collected. For this purpose, discharge (cfs) for each USGS station was converted to runoff (mm /day) to normalize for unequal basin area.

RESULTS AND DISCUSSION

Table 3 lists the range and interquartile distributions of analyte concentration values for VTSSS stream water sampling sites in the St. Marys River watershed. ANC values for VTSSS monitoring sites in the St. Marys River watershed are plotted with time in Fig. 2.

The USDA Forest Service has devised ANC criteria for evaluation of potential acidification effects on aquatic biota (Adams et al., 1991). An ANC value of 25 µeq/L was identified as the approximate lower limit of the range of ANC over which it is reasonably certain that fish and other aquatic organisms will not be affected by low pH and elevated aluminum concentrations. An ANC value of 10 µeq/L was identified as the value below which long-term exposure will likely cause adverse biological effects. An ANC value of 0 µeq/L was identified as the value below which short-term exposure will likely cause adverse biological effects. Consistent with observed losses of fish and macroinvertebrate taxa (Kauffman et al., 1999; Bugas et al., 1999), many of the ANC values for St. Marys River (Table 3 and Fig. 2) are below the indicated criteria for adverse affects on aquatic biota.

Fig. 2 also reveals the presence of both spatial and temporal variation in surface water ANC values in the watershed. In general, lower ANC values occur at sites in the upper part of the watershed and on tributaries draining from the north. These differences are consistent with associations between bedrock geology and stream water ANC observed in other areas of the Blue Ridge Moun-

tains (Lynch & Dise, 1985). Based on these associations, ANC values for stream waters draining the different bedrock formations in the watershed would be expected to decrease in the following order: Catoctin > Unicoi > Hampton > Antietam. This pattern is clearly evident in the distribution of stream water ANC values observed for the synoptic surveys. In Fig. 3, the ANC values for the March 1992 survey sites are displayed in relation to the mapped geologic formations. In general, the spatial variation of ANC in the watershed can be explained as a function of base-cation availability in the different rocks and associated soils. However, another factor may contribute to the relatively high ANC values in stream water draining the Shady Formation. Sulfate concentrations in these streams range from 5-15 μeq/L. This range is in the low end of the distribution observed for the synoptic surveys and much lower than the values observed for the quarterly monitoring sites (see Table 3). We suggest that the residual clay minerals associated with this formation may have an exceptionally high capacity for retention of atmospherically deposited sulfate. If so, this could affect ANC by altering the balance between concentrations of acid-anions and base-cations.

Several components of temporal variation are also apparent in Fig. 3. As commonly observed for upland surface waters (Baker et al., 1990b), cold season ANC values are generally lower than warm season values. Superimposed on this seasonal pattern is short-term variation determined by variation in discharge. This component is most apparent in the weekly data collected at VT41. Although discharge measurements are not available to allow direct examination of the flow-concentration relationship at this site, investigations in similar areas of the Blue Ridge Mountains (e.g., Eshleman et al., 1995) have shown that the lowest stream water ANC values occur on an episodic basis in association with high-discharge conditions.

Seasonal and episodic variation in the ANC of St. Marys River occur in a context of long-term or chronic change in ANC. In order to evaluate this change we performed trend analysis on the 10 years of quarterly data available for VT41. This analysis was performed in two steps using simple linear regression (SAS, 1991). Step one involved removal of background variation or "noise" related to discharge. As a preliminary step, we confirmed that there was no trend in estimated runoff during the 10-year period. Regression analysis was then applied to test the association between ANC and the estimated runoff values. This test was significant at $P<0.001$. Step two was performed by application of regression analysis to test the association between time and the residuals of step one (interpreted as variation in ANC over and above that due to variation caused by changes in runoff). This test was significant at $P<0.01$, with an estimated slope of -0.50 μeq/L/yr (Fig. 4). Additional tests were performed on the remaining residuals to confirm normality and constant error variance.

Based on the described trend analysis, the ANC of St. Marys River at site VT41 declined 5 μeq/L during the period of 1988-1997. This change is substantial in relation to both the median ANC value of 4.4 μeq/L for the 10-year period (Table 3) and the above cited USDA Forest Service criterion value of 0 μeq/L for adverse biological affects given short-term exposure. It is also consistent with expectations of further acidification of central Appalachian streams due to elevated levels of atmospheric sulfur deposition. Cosby et al. (1991), Church et al. (1992), and Herlihy et al. (1993) have predicted that streams in this region will lose ANC as sulfur retention in watershed soils decreases over time. However, attribution of specific cause for the observed ANC change during this particular 10-year period will require additional analysis. Interpretation is complicated by dramatic alteration of stream water composition related to forest defoliation by the gypsy moth. Webb et al. (1995) and Eshleman et al. (1998) have documented changes in concentrations of nitrate, sulfate, base cations, and hydrogen ion that persisted for several years or more following defoliation. Until additional progress is achieved in modeling these effects, it will be difficult to partition the contributions of acidic deposition and forest defoliation to recent ANC change in the St. Marys River.

CONCLUSIONS

Stream water ANC in most of the St. Marys River watershed is below recognized criteria values for probability of adverse effects on aquatic fauna. Spatial variation in stream water ANC within the watershed is explained largely by the distribution of different bedrock types. Although it is clear that St. Marys River has experienced biologically significant acidification during the period of 1988-1997, the relative roles of acidic deposition and forest defoliation as causes for this acidification have not been determined.

ACKNOWLEDGEMENTS

Financial and logistical support for VTSSS data collection and analysis has been provided by the Virginia Department of Game and Inland Fisheries, the USDA Forest Service, the U.S. Environmental Protection Agency, the National Park Service, and Trout Unlimited.

Table 3. Summary statistics (range and interquartile distribution) for analyses of stream water composition in the St. Marys River watershed.

ID	TYPE	START	STOP	N	MIN	25%	MED	75%	MAX
ANC (μeq/L)									
VT41	QUARTERLY	10/26/87	7/28/97	40	-8.1	1.2	4.4	6.9	15.4
VT41	WEEKLY	6/21/88	12/27/93	252	-27.9	2.8	6.2	8.7	20.3
VT68	QUARTERLY	6/21/88	10/28/93	21	-13.8	-10.6	-8.4	-7.2	-2.1
VT69	QUARTERLY	1/30/89	10/28/93	20	1.5	3.6	6.3	10.4	19.4
VT70	QUARTERLY	1/30/89	10/28/93	20	2.4	6.2	7.9	12.8	23.7
VT71	QUARTERLY	1/30/89	10/28/93	20	-6.8	1.2	3.2	7.0	16.2
VT72	QUARTERLY	1/30/89	7/28/93	8	-13.0	-7.2	-6.4	-4.7	-3.8
VT73	QUARTERLY	6/21/88	10/28/93	21	6.2	9.9	18.1	28.1	47.9
VT74	QUARTERLY	1/30/89	10/28/93	20	-3.9	-1.3	0.9	5.3	16.9
SYN1	SYNOPTIC	3/28/92	3/28/92	61	-19.7	-0.2	5.3	13.3	47.5
SYN2	SYNOPTIC	4/24/93	4/24/93	45	-25.0	-7.2	2.4	10.3	25.3
pH									
VT41	QUARTERLY	10/26/87	7/28/97	40	5.1	5.5	5.7	5.8	6.1
VT41	WEEKLY	6/21/88	12/27/93	252	5.1	5.6	5.8	5.9	6.8
VT68	QUARTERLY	6/21/88	10/28/93	21	4.9	5.0	5.1	5.1	5.3
VT69	QUARTERLY	1/30/89	10/28/93	20	5.3	5.7	5.8	5.9	6.0
VT70	QUARTERLY	1/30/89	10/28/93	20	5.2	5.8	5.9	5.9	6.1
VT71	QUARTERLY	1/30/89	10/28/93	20	5.5	5.6	5.7	5.8	6.0
VT72	QUARTERLY	1/30/89	7/28/93	8	5.0	5.0	5.1	5.3	5.3
VT73	QUARTERLY	6/21/88	10/28/93	21	5.3	5.9	6.0	6.2	6.4
VT74	QUARTERLY	1/30/89	10/28/93	20	5.2	5.5	5.6	5.8	6.2
SYN1	SYNOPTIC	3/28/92	3/28/92	61	4.7	5.3	5.8	6.1	6.6
SYN2	SYNOPTIC	4/24/93	4/24/93	45	4.6	5.1	5.6	6.1	6.4
Calcium (μeq/L)									
VT41	QUARTERLY	10/26/87	7/28/97	40	20.4	22.0	22.8	24.4	27.6
VT41	WEEKLY	6/21/88	12/27/93	252	17.8	22.1	23.7	25.0	45.5
VT68	QUARTERLY	6/21/88	10/28/93	21	9.7	12.2	13.0	13.5	15.7
VT69	QUARTERLY	1/30/89	10/28/93	20	16.0	17.2	18.0	18.8	20.3
VT70	QUARTERLY	1/30/89	10/28/93	20	17.1	18.7	20.0	20.7	22.5
VT71	QUARTERLY	1/30/89	10/28/93	20	15.0	16.2	17.2	18.0	19.6
VT72	QUARTERLY	1/30/89	7/28/93	8	12.5	14.0	17.4	19.0	21.6
VT73	QUARTERLY	6/21/88	10/28/93	21	23.2	30.6	32.2	37.3	42.3
VT74	QUARTERLY	1/30/89	10/28/93	20	16.7	19.3	20.9	21.8	23.6
SYN1	SYNOPTIC	3/28/92	3/28/92	61	4.6	14.4	18.4	24.5	45.9
SYN2	SYNOPTIC	4/24/93	4/24/93	45	9.4	14.5	16.8	24.0	43.5

Table 3. Continued.

ID	TYPE	START	STOP	N	MIN	25%	MED	75%	MAX
Magnesium (μeq/L)									
VT41	QUARTERLY	10/26/87	7/28/97	40	25.7	27.1	28.1	30.3	33.7
VT41	WEEKLY	6/21/88	12/27/93	252	23.4	27.2	29.3	30.9	57.0
VT68	QUARTERLY	6/21/88	10/28/93	21	15.5	18.0	18.8	19.5	20.4
VT69	QUARTERLY	1/30/89	10/28/93	20	21.6	22.8	24.4	25.0	26.0
VT70	QUARTERLY	1/30/89	10/28/93	20	20.1	21.8	22.9	23.6	24.8
VT71	QUARTERLY	1/30/89	10/28/93	20	21.0	22.6	23.8	24.3	26.3
VT72	QUARTERLY	1/30/89	7/28/93	8	17.8	18.6	21.7	23.7	26.6
VT73	QUARTERLY	6/21/88	10/28/93	21	28.6	37.3	39.4	41.8	52.1
VT74	QUARTERLY	1/30/89	10/28/93	20	21.8	24.3	25.6	26.8	28.4
SYN1	SYNOPTIC	3/28/92	3/28/92	61	9.9	20.4	24.2	29.8	44.4
SYN2	SYNOPTIC	4/24/93	4/24/93	45	14.8	20.8	23.9	29.7	40.4
Sodium (μeq/L)									
VT41	QUARTERLY	10/26/87	7/28/97	40	15.5	16.9	17.4	17.8	20.5
VT41	WEEKLY	6/21/88	12/27/93	252	13.0	16.8	17.4	18.0	24.3
VT68	QUARTERLY	6/21/88	10/28/93	21	13.8	14.5	15.4	15.9	19.0
VT69	QUARTERLY	1/30/89	10/28/93	20	16.6	17.2	17.9	18.6	19.2
VT70	QUARTERLY	1/30/89	10/28/93	20	15.3	16.0	16.9	17.3	17.9
VT71	QUARTERLY	1/30/89	10/28/93	20	15.2	15.8	16.9	17.7	18.4
VT72	QUARTERLY	1/30/89	7/28/93	8	13.7	14.4	15.2	16.1	17.1
VT73	QUARTERLY	6/21/88	10/28/93	21	19.7	20.9	22.1	23.1	25.2
VT74	QUARTERLY	1/30/89	10/28/93	20	14.4	15.0	15.5	16.3	17.3
SYN1	SYNOPTIC	3/28/92	3/28/92	61	12.1	14.8	16.1	17.7	24.4
SYN2	SYNOPTIC	4/24/93	4/24/93	45	12.1	14.5	15.9	17.1	23.8
Potassium (μeq/L)									
VT41	QUARTERLY	10/26/87	7/28/97	40	14.2	16.3	17.2	18.3	20.4
VT41	WEEKLY	6/21/88	12/27/93	252	11.8	16.4	17.4	18.6	32.9
VT68	QUARTERLY	6/21/88	10/28/93	21	8.2	11.2	12.0	12.9	14.2
VT69	QUARTERLY	1/30/89	10/28/93	20	18.7	22.6	23.5	25.1	26.6
VT70	QUARTERLY	1/30/89	10/28/93	20	15.0	18.1	19.3	20.8	22.9
VT71	QUARTERLY	1/30/89	10/28/93	20	16.7	18.8	20.4	22.9	25.4
VT72	QUARTERLY	1/30/89	7/28/93	8	12.8	17.9	18.8	20.3	21.2
VT73	QUARTERLY	6/21/88	10/28/93	21	21.1	24.3	25.2	27.2	31.8
VT74	QUARTERLY	1/30/89	10/28/93	20	12.1	14.4	15.1	16.4	20.3
SYN1	SYNOPTIC	3/28/92	3/28/92	61	4.0	13.7	16.7	22.1	28.8
SYN2	SYNOPTIC	4/24/93	4/24/93	45	5.3	14.9	17.6	24.2	30.8
Sulfate (μeq/L)									
VT41	QUARTERLY	10/26/87	7/28/97	40	50.1	53.8	61.9	65.3	74.1
VT41	WEEKLY	6/21/88	12/27/93	252	46.5	53.5	60.9	65.1	114.1
VT68	QUARTERLY	6/21/88	10/28/93	21	46.5	49.9	54.6	56.4	62.7
VT69	QUARTERLY	1/30/89	10/28/93	20	45.1	48.6	54.4	56.5	59.6
VT70	QUARTERLY	1/30/89	10/28/93	20	36.8	39.1	45.2	47.8	52.6
VT71	QUARTERLY	1/30/89	10/28/93	20	44.6	47.8	52.1	54.2	57.2
VT72	QUARTERLY	1/30/89	7/28/93	8	48.0	49.2	60.4	66.3	75.4
VT73	QUARTERLY	6/21/88	10/28/93	21	65.2	70.2	74.3	76.5	91.3
VT74	QUARTERLY	1/30/89	10/28/93	20	42.9	46.0	57.4	60.5	66.9
SYN1	SYNOPTIC	3/28/92	3/28/92	61	5.0	44.9	55.1	60.8	84.2
SYN2	SYNOPTIC	4/24/93	4/24/93	45	28.1	47.5	61.4	65.5	92.9

Table 3. Continued.

ID	TYPE	START	STOP	N	MIN	25%	MED	75%	MAX
Nitrate (μeq/L)									
VT41	QUARTERLY	10/26/87	7/28/97	40	0.0	0.0	0.2	2.4	6.7
VT41	WEEKLY	6/21/88	12/27/93	252	0.0	0.2	0.3	2.8	16.5
VT68	QUARTERLY	6/21/88	10/28/93	21	0.0	0.1	0.2	0.2	1.2
VT69	QUARTERLY	1/30/89	10/28/93	20	0.0	0.1	0.2	2.0	7.9
VT70	QUARTERLY	1/30/89	10/28/93	20	0.0	0.1	0.2	3.3	7.9
VT71	QUARTERLY	1/30/89	10/28/93	20	0.0	0.1	0.2	1.1	5.9
VT72	QUARTERLY	1/30/89	7/28/93	8	0.1	0.1	0.2	0.2	1.1
VT73	QUARTERLY	6/21/88	10/28/93	21	0.0	0.1	0.4	7.2	15.0
VT74	QUARTERLY	1/30/89	10/28/93	20	0.0	0.1	0.2	0.9	4.1
SYN1	SYNOPTIC	3/28/92	3/28/92	61	0.1	0.4	1.5	4.1	22.3
SYN2	SYNOPTIC	4/24/93	4/24/93	45	0.3	1.1	1.9	8.0	25.5
Chloride (μeq/L)									
VT41	QUARTERLY	10/26/87	7/28/97	40	14.7	15.7	16.3	17.5	21.3
VT41	WEEKLY	6/21/88	12/27/93	252	11.5	15.5	16.2	16.8	34.3
VT68	QUARTERLY	6/21/88	10/28/93	21	13.9	14.3	15.4	15.8	16.8
VT69	QUARTERLY	1/30/89	10/28/93	20	13.3	14.3	15.2	15.7	17.2
VT70	QUARTERLY	1/30/89	10/28/93	20	13.5	14.3	15.1	15.6	16.5
VT71	QUARTERLY	1/30/89	10/28/93	20	13.5	13.9	14.7	15.3	16.9
VT72	QUARTERLY	1/30/89	7/28/93	8	14.1	14.2	14.9	15.6	15.7
VT73	QUARTERLY	6/21/88	10/28/93	21	15.3	16.3	17.3	18.3	19.5
VT74	QUARTERLY	1/30/89	10/28/93	20	14.1	14.7	15.4	15.7	16.4
SYN1	SYNOPTIC	3/28/92	3/28/92	61	12.8	14.5	15.0	16.2	21.8
SYN2	SYNOPTIC	4/24/93	4/24/93	45	12.2	14.1	14.9	16.4	19.8
Silica (μm/L)									
VT41	QUARTERLY	10/26/87	7/28/97	40	62.4	67.4	71.9	85.2	94.5
VT41	WEEKLY	6/21/88	12/27/93	252	54.0	69.0	74.7	83.7	101.4
VT68	QUARTERLY	6/21/88	10/28/93	21	53.6	58.0	62.7	70.4	76.1
VT69	QUARTERLY	1/30/89	10/28/93	20	64.8	68.2	69.8	76.9	91.8
VT70	QUARTERLY	1/30/89	10/28/93	20	62.7	65.1	67.5	77.5	90.0
VT71	QUARTERLY	1/30/89	10/28/93	20	60.8	63.4	67.6	77.7	87.3
VT72	QUARTERLY	1/30/89	7/28/93	8	59.6	65.0	69.9	79.0	89.0
VT73	QUARTERLY	6/21/88	10/28/93	21	74.8	78.8	81.8	91.9	97.1
VT74	QUARTERLY	1/30/89	10/28/93	20	58.4	65.0	68.3	82.8	97.0
SYN1	SYNOPTIC	3/28/92	3/28/92	61	49.4	59.6	63.0	67.2	87.5
SYN2	SYNOPTIC	4/24/93	4/24/93	45	43.8	58.3	61.4	64.9	81.2
Total Monomeric Aluminum (μg/L)									
VT41	QUARTERLY	1/26/94	4/28/97	14	11.6	13.8	19.3	31.9	66.0

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Effects of Acidification on Benthic Fauna in St. Marys River, Augusta County, Virginia

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INTRODUCTION

The impacts of acidification on aquatic organisms have been well documented in the literature (Magnunson, 1983). Griffith & Perry (1992) summarized the literature on the effects of acidification on benthic invertebrates and reported that acid sensitive species decline in abundance, acid tolerant species increase in abundance, number of species decline, and community biotic diversity decreases. Three primary methods have been utilized by researchers to assess biotic changes from acid deposition: experimental acidification, spatial comparisons between geographically similar waters with differing water chemistry, and temporal comparisons of a resource. Temporal comparisons, however, are rarely documented due to the lack of long-term data sets.

Documented biological changes due to acid deposition in invertebrate communities have been limited to northern states, Canada, and Scandinavian countries. This is expected since these areas are considered more sensitive to acidification due to loss of soils from glaciation. Despite the lack of glaciation, waters in southern states are sensitive because of their underlying geology and streams with low acid neutralization capacity have been documented (Herlihy et al., 1993). Lasier (1986) was unable to document any biological impacts to southern streams due in part to the lack of historical data.

The St. Marys River in Virginia provides the opportunity to temporally assess the impacts of acid deposition on a southeastern USA stream. Historic invertebrate and water chemistry data exist from 1936 and 1937 (Surber, 1951). Recent invertebrate data have been collected by Virginia Department of Game and Inland Fisheries (VDGIF) personnel starting in 1976 as part of the Virginia trout stream survey. The historic data from Surber and VDGIF provide a unique opportunity to compare reliable invertebrate data on an acidified stream drainage over a 60-year time span. The stream was once a premier wild trout stream but has been degraded by the impacts of anthropomorphic acidification (Webb & Diviney, 1999).

STUDY AREA

St. Marys River is a third order coldwater stream that drains the west slope of the central Blue Ridge Mountains in southeastern Augusta County, Virginia. It forms the southwest boundary of the Big Levels Management Area and its 27 km^2 watershed is the centerpiece of the 4,000 hectare St. Marys Wilderness Area. St. Marys River originates at 951 m above sea level and descends at a gradient of 39 m/km to its confluence with Spy Run, 11.4 km downstream.

The watershed is comprised of five major tributaries (Fig. 1). St. Marys River's low ANC levels can be traced to the geologic formations that underlie the watershed (Webb & Diviney, 1999). Antietam quartzite is the primary rock formation (Werner, 1966). Formations of Hampton quartzite underlie the upper watersheds of Sugartree Branch, Mine Bank Creek, Bear Branch, and Chimney Branch, as well as the lower reach of St. Marys River. Both formations are known to have low solubility in water, thus providing few reactive materials to neutralize acidic input (Webb & Diviney, 1999).

Dominant overstory vegetation in the St. Marys River basin include chestnut oak (*Quercus prinus*) and scarlet oak (*Quercus coccinea*) on ridges and north aspects, with pitch pine (*Pinus rigida*) and table mountain pine (*Pinus pungens*) dominating the southern and western slopes. Understory plants include mountain laurel (*Kalmia latifolia*), bear oak (*Quercus ilicifolia*), rhododendron (*Rhododendron maximum*), dogwood (*Cornus florida*), red maple (*Acer rubrum*), and black gum (*Nyssa

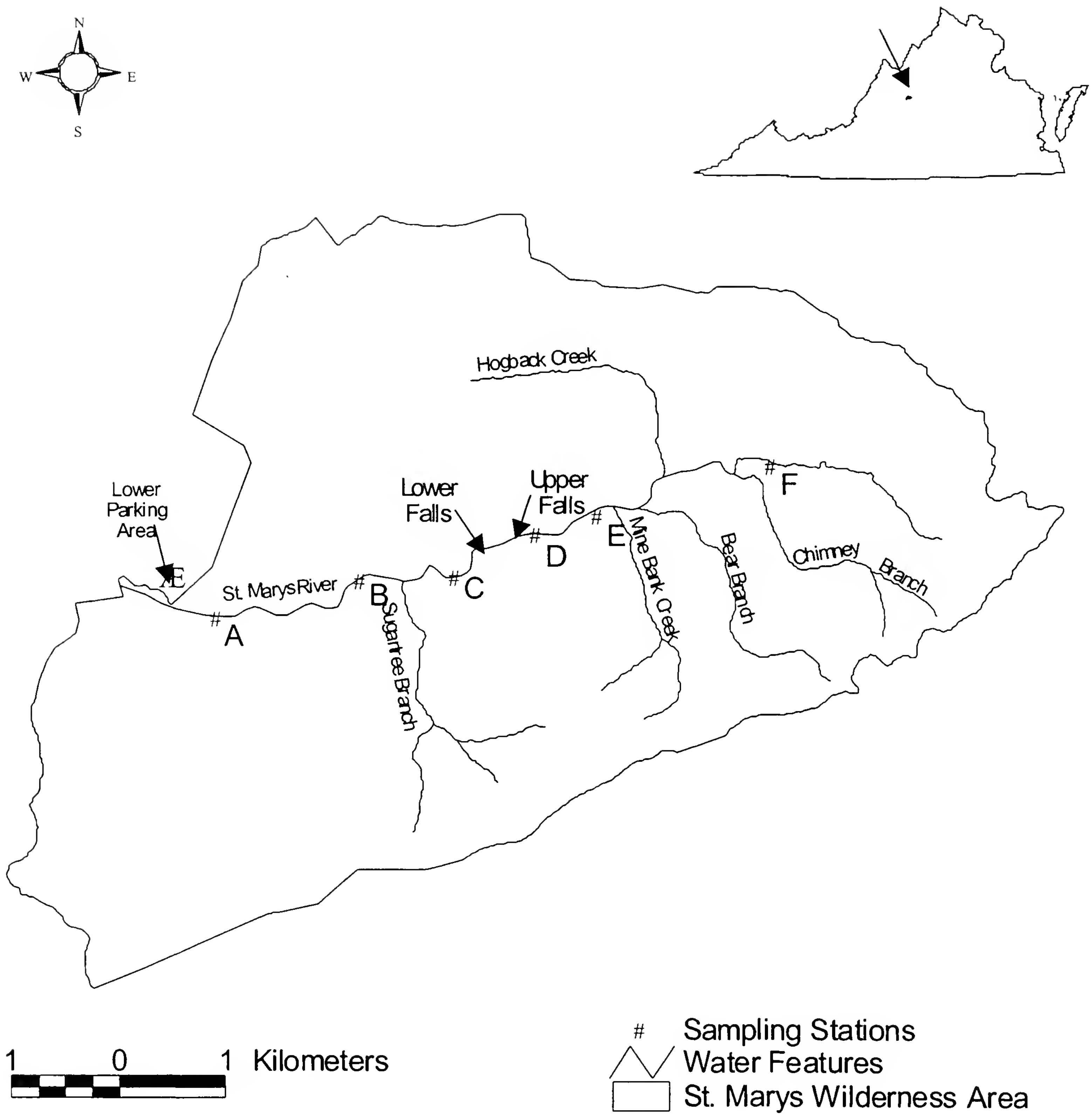

Fig. 1. Department of Game and Inland Fisheries biological sampling stations in the St Marys River, Augusta County, Virginia.

sylvatica). Well drained, sandy loam covers most of the watershed, with the primary soil type being Drall-Hazleton-Leetonia (Hockman et al., 1979). It is considered to be poor, acidic soil. St. Marys has been classified as acidic and has lost the ability to successfully maintain a pH range that will support a diversity of aquatic life (Webb & Deviney 1999). The geology and commercial, scientific, and management history of the study area has been described by Bugas et al. (1999), Bank et al. (1999) and Swartz et al. (1999).

MATERIALS AND METHODS

Surber (1951) collected basic water chemistry in his early St. Marys River study but did not report the method

used for pH determination or the collection sites, however, electronic and color comparator methods were available at that time. Trout Unlimited used a color comparator for determination in 1974 (G. D. Schuder, unpublished letter to VDGIF, 1976). Mohn (1980) used a color comparator for pH determinations in 1976. We recently compared readings by the color comparator to samples analyzed electronically at the University of Virginia. Readings were 0.5 to 1.0 units higher than those from the electronic pH meter. Since this difference can span ± 0.5 pH units, we left the 1974 and 1976 data uncorrected. Starting in 1986, water samples were collected quarterly and pH was determined electronically as part of the Virginia Trout Stream Sensitivity Study (Webb et al., 1994).

Surber collected twenty 0.09 m^2 samples per month for two years starting in August 1935 (Surber, 1951). Mesh size was 1 mm. Only his June samples were used since collections in later years were made only in June. Surber reported the data in defined taxa with a miscellaneous group for each order. Taxonomic names Surber reported were corrected to current classifications using Merritt & Cummins (1984).

Mohn (1980) described the use of the Carle sampler to collect invertebrates. One sample (0.27 m^2) was collected at each of the six sampling locations (Fig. 1). Mesh size was 1 mm. Sampling sites were located at evenly spaced intervals from the lower St. Marys Wilderness boundary to the headwaters. Total sample area per collection year was 1.6 m^2. Carle (1976) compared his sampler to the Surber sampler and concluded that invertebrate diversity was similar if the surface area sampled exceeded 1 m^2. Carle concluded that his sampler with one run (as opposed to a three run depletion) provided higher invertebrate densities (an average of 31%), although the differences were not statistically significant. Carle documented no species selectivity by his sampler. In our study, identification was to genus or species but taxa were combined to fit those categories reported by Surber for this comparison.

The Shannon diversity index, equitability index, EPT index, and Rapid Bioassessment III protocols were used to evaluate community health as described by Klemm et al. (1990). The EPT index is a total of the Ephemeroptera, Plecoptera, and Trichoptera taxa collected. These three orders are considered to be pollution intolerant and serve as good indicators of community change. Rapid Bioassessment III compares a stream to a reference section that is in good health and involves an integrated analysis of both functional and structural components of the aquatic invertebrate community. For this analysis, the 1936-37 sample was averaged and used as the reference site. Seven metrics comprise the RBP-III: taxa richness, modified Hilsenhoff biotic Index, ratio of scrapers to collector-filterers, ratio of EPT's to chironomids, percent contribution of the dominant taxon, EPT index, and community loss index. Any changes reflect the temporal impacts of acidification.

RESULTS AND DISCUSSION

Water pH declined over time with no values recorded above 6.0 after 1992 (Table 1). Prior to 1988, only one sample had a value below 6.0. Several recent samples have had readings below 5.2. Pre-industrial pH of precipitation in Virginia has been estimated to be from 5.3 to 5.6 (Webb, 1987). In 1996, precipitation pH readings at the Big Meadows water monitoring station in Shenandoah National Park, Madison Co., Virginia averaged 4.4 (US Environmental Protection Agency, 1998). The low buffering capacity of the watershed has resulted in pH readings closely paralleling rainfall pH.

Changes in the invertebrate taxa over the sixty-year period can be grouped into four categories: unchanged, extirpated, declined, and increased. Values of 0.6 individuals m^2 represent the collection of a single individual (Table 2).

Table 1. Range of pH values collected from 1936 to 1996 in the St. Marys River, Augusta County, Virginia.

Year	High	Low
1938	6.9	6.7
1974*	7.0	6.7
1976 (one sample)*	7.0	
1988	6.10	5.20
1990	6.12	5.54
1992	6.07	5.16
1994	5.97	5.51
1996	5.70	5.12

*Values were by colormetric determination. Comparison of this method with later electronic analysis indicates readings are 0.5 to 1.0 units high.

Table 2. Number of benthic macroinvertebrates collected per square meter in the St. Marys River from 1936 to 1998. Renamed original taxa are indicated by the old name in parenthesis. Blank spaces indicate that no indivduals were collected.

TAXA	1936	1937	1976	1986	1988	1990	1992	1994	1996	1998
Oligochaeta	5.4	1.1	3.8	0.0	1.8	3.8	0.0	1.8	16.2	4.9
Crustacea										
Cambarus	7.5	4.8	1.3	0.6	3.1	2.5	1.3	6.2	0.6	0.0
Trichoptera										
Cheumatopsyche/Hydropsych	73.7	26.4	11.3	8.2		1.8	5.6		1.3	2.5
Dolophilodes	60.3	7.5	0.0	3.7			2.5			0.6
Rhyacophila	13.5	7.0	4.4			0.6	0.6	3.8	3.1	0.6
Brachycentrus	0.5	2.2			8.2	6.9	0.6			1.8
Misc. Trichoptera	19.9	3.2	20.7				10.7	9.4		12.5
Plecoptera										
Leuctra, Alloperla etc.	15.6	12.4	331.0	75.1	55.1	171.1	521.9	402.2	282.1	258.2
Peltoperla	7.5	1.1	22.5	0.6	0.6			1.3	5.1	30.1
Perla & Acroneura	23.1	17.2	4.9	1.3	1.3	0.6	3.1		1.8	
Pteronarcys	4.8	1.6	1.3							3.1
Nemoura	5.9	0.5								
Misc. Plecoptera	1.1		104.5	3.1	4.9	3.1	27.5	6.2	10.7	11.3
Odonata										
Lanthus	0.5									1.3
Misc. Odonata	0.5		2.5				1.8	1.3	1.3	0.0
Ephemeroptera										
Stenonema	30.7	16.1	12.5	1.3	1.3			8.2	3.8	3.1
Baetis & Pseudocleon	32.3	30.7	19.4	6.9		10.7	0.6	8.2	4.4	6.9
Paraleptophlebia	21.0	55.4	0.6							
Epeorus (Iron)	80.7	33.4	0.6							
Ephemerella	74.8	17.2	0.6						1.3	0.6
Isonychia	1.1		0.6						0.6	
Misc. Ephemeroptera	0.0	2.2			5.6		3.1	1.3	0.6	1.3
Megaloptera (Neuroptera)										
Nigronia	5.7	6.5	1.3		4.4		4.4	8.7	1.3	5.6
Coleoptera										
Elmidae (Parnid)	1.6	1.6	14.4	2.5	5.6	1.8	1.3	5.1	1.8	13.8
Psephenus	0.5	1.1								
Misc. Coleoptera	2.2	2.7								
Diptera										
Atherix	5.4	13.5								0.6
Chironomidae	61.9	35.5	281.9	35.1	128.3	164.6	167.9	183.2	303.4	642.4
Hexatoma (Erioica)	5.4	7.5	9.4							
Simulium	15.6	11.3	14.4		1.3	0.6	52.5	2.5	4.4	20.4
Antocha	2.7	1.6	3.1	2.5	0.6					
Misc. Diptera	3.8	1.6	0.0		0.6		5.1	5.6	0.6	8.7
Miscellaneous invertebrat	0.5	1.1	0.0	0.6	0.6	3.1		0.6	3.1	8.1
TOTAL ABUNDANCE	585.7	323.9	867.0	141.5	224.8	371.3	810.6	655.6	647.8	1038.0
NUMBER OF TAXA	32	29	23	13	19	13	17	17	20	22
EPT TAXA	17	16	14	8	9	7	10	8	10	13
DIVERSITY (Shannon)	3.94	3.96	2.66	2.12	2.02	1.65	1.69	1.67	1.69	1.8
EQUIBILITY (e)	0.72	0.79	0.35	0.46	0.26	0.3	0.23	0.23	0.2	0.18
% Biological Cond. Score	Averaged		71	48	38	38	57	52	52	52

Unchanged Taxa

Taxa that were unchanged showed considerable variation but no apparent trend in abundance (Table 2). These include: Oligochaeta, *Cambarus* (crayfish), *Brachycentrus* (American grannon), *Peltoperla* (roachlike stonefly) *Isonychia* (brushlegged mayfly), *Nigronia* (fish flies), *Elmidae* (riffle beetles), and *Simulium* (black fly). Miscellaneous Trichoptera, Odonata, Ephemeroptera, and Diptera showed no apparent trends. Smith et al. (1990) and Simpson et al. (1985) reported elmids (Coleoptera) to be acid tolerant but that they decline when pH falls below 6.0. Townsend et al. (1983), however, found no correlation between the abundance of elmids and the pH of streams in England.

Declined Taxa

Declining taxa showed varying responses. In all cases numbers collected between 1976 and 1998 were fewer than observed in the 1936 and 1937 samples (Table 2). Trichoptera taxa included *Cheumatopsyche/Hydropsyche* (common netspinners), *Dolophilodes* (fingernet caddisfly) and *Rhyacophila* (green sedge). *Dolophilodes* were collected only three times since 1976. Peterson & VanEeckhaute (1992) reported that *Rhyacophila* were found in acidic streams but *Dolophilodes* were not observed in streams when summer pH was less than 5.9.

Considering stoneflies (Plecoptera), *Perla/Acroneuria* (common stonefly) and *Pteronarcys* (giant black stonefly) have declined in the river with *Pteronarcys* being collected only in 1936, 1937, 1976, and 1998. Griffith & Perry (1992) collected *Acroneuria* in West Virginia streams when pH was 7.5, but not in streams below 6.2.

Mayflies (Ephemeroptera) showed the greatest decline in the St. Marys River, similar to other literature reports on this order. *Stenonema* (March brown), *Baetis/Pseudocloen* (small minnow mayfly and skimmer) and *Ephemerella* (sulphur) were very abundant in 1936 and 1937 but have declined substantially, with *Ephemerella* collected only three times from the last eight samples. Feldman (1986) observed that *Stenonema* had greater tolerance to acidity than *Ephemerella,* and that *Epheme-rella* was low or absent in low alkalinity streams. The limiting pH for *Ephemerella* is 5.5 to 5.7 and for *Baetis* is 5.7 to 6.0 (Peterson & VanEeckhaute, 1992). Fiance (1978) observed that *Ephemerella funeralis* was absent when pH was <5.5. Smith et al. (1990) observed that *Baetis* occurred only when pH was >5.4.

Extirpated Taxa

Some taxa have been extirpated from the St. Marys River. The stonefly (Plecoptera) *Nemoura* (nemourid broadbacks) and the Coleoptera *Psephenus* (water penny) have not been collected since 1936 and 1937. The mayflies *Paraleptophlebia* (dark blue quill) and *Epeorus* (quill gordon) were last collected in 1976 and their numbers were substantially reduced from the 1936 and 1937 collections. Peterson & VanEeckhaute (1992) reported that the limiting pH for *Epeorus* was 5.7-6.0. Lasier (1986) observed that *Epeorus* abundance was correlated with stream pH. Feldman (1986) also observed that *Paraleptophlebia* and *Epeorus* were absent in low alkalinity streams.

The dipteran, *Antocha* (crane fly) was last collected in 1988 but prior to that its numbers were stable over the years. *Atherix* (watersnipe fly) has not been collected since the 1936 and 1937 samples except for one individual in 1998. *Hexatoma* (crane fly) has not been collected since 1976.

Increased Taxa

Only three taxa have increased in abundance (Table 2). Two of these were Plecoptera: *Leuctra/Alloperla* (rolledwinged stonefly/green stonefly) and miscellaneous Plecoptera. Increased abundance of *Leuctra* in acidified waters is one of the most documented changes observed (Fiance, 1979; Arnold et al., 1981; Townsend et al., 1983; Kimmel & Murphy, 1985; Simpson et al., 1985; Lasier, 1986; Smith et al., 1990).

The abundance of Chironomidae (midges) has increased at least five fold since the 1936 and 1937 collections. Chironomidae increase is also a well-documented change in acidified waters (Hall et al., 1980; Townsend et al., 1983; Kimmel & Murphy, 1985; Lasier, 1986).

Increased abundance of these taxa is the result of several factors. The first is the resistance to low pH, as reported in the above studies. A second factor may be reduced competition from taxa that are not tolerant to low pH. As these acidophobic taxa are reduced in numbers, increased niches may be available for acidophilic taxa.

Community Structure

Total numbers of individuals collected have generally increased, although the lowest abundance occurred in 1986 (Table 2). The increase may be an artifact of the different sampling methods. However, most of this increase and shift occurred in the acid tolerant taxa Chironomidae and *Leuctra/Alloperla.* In the 1930s, these two taxa together comprised only 10-20% of the community but now comprise around 90%. The low abundance in 1986 may reflect the impact of a major flood in 1985. A flood also occurred in 1937 before Surber's sampling that year and may have caused the decline from 1936.

The numbers of taxa were highest in 1936-37, slightly lower in 1976, and have held steady since 1976 (Table 2). Much of the reduction in numbers of taxa collected has occurred in the EPT taxa. Ephemeroptera have been well documented as declining in species abundance and richness with a decrease in pH (Mackay & Kersey, 1985; Burton & Allan, 1986; Peterson & Van Eeckhaute, 1992; Kobuszewski & Perry, 1993).

Shannon diversity index values also declined (Table 2). Highest values were in 1936-37 at 4.0. Diversity continued to decline from 1976 through 1988. Since 1988, all diversity values have been below 2.0 with a slight improvement in 1998. Unpolluted waters generally have values between 3 and 4 (Klemm et al., 1990). Values observed in 1936-37 reflect a healthy environment that has since declined over time.

The equitability index was highest in 1936-37 and declined since those samples were taken (Table 2). Unpolluted waters have values above 0.5 whereas stressed waters have values 0.3 or lower (Klemm et al., 1990). Since 1988, the system is rated as being stressed. Even though diversity increased slightly in 1998, the equitability index declined to its lowest value that year. Similar declines in species richness, diversity, and equitability have been observed in other Appalachian and Adirondack acidic streams (Hall et al., 1980; Arnold et al., 1981; Burton et al., 1982; Kimmel, 1985; Simpson et al., 1985; Feldman, 1986; Peterson & VanEeckhaute, 1992).

Bioassessment scores declined from average values in 1936-37 (Table 2). The decline was first observed in 1976. That year (value of 71) would be rated as slightly impaired by Plafkin (1989) compared to the 1936-37 sample. Values after 1976 declined further, the lowest values being observed in 1988 and 1990 at 38. In 1992, the percent comparability to the reference score was 57, giving a rating of slightly impaired. All other years since 1976 (except 1992) are rated as moderately impaired.

Our documented changes in the macroinvertebrate community in the St. Marys River provide the first documented impact of temporal changes in acidification on a southeast U.S.A. stream. The observed changes in the invertebrate fauna are consistent with those reported in the literature for streams with low pH. Taxa such as *Epeorus*, *Ephemerella*, *Paraleptophlebia*, and *Stenonema*, which have been identified as being acid intolerant, have declined in the St. Marys River. Acid tolerant taxa such as *Leuctra* and Chironomidae increased. Community structure and complexity declined as a result of the stress of anthropogenic acidification. Our data clearly demonstrate that biological degradation as a result of acid deposition has occurred in St. Marys River and may reflect conditions in the southern Appalachian Mountains.

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Impacts of Acid Deposition on Fish Populations in St. Marys River, Augusta County, Virginia

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INTRODUCTION

Acid deposition, which includes rain, drizzle, fog, sleet, snow and dry particulate matter, has been impacting aquatic ecosystems in the mid-Atlantic and southeastern United States for at least the past two decades (Herlihy et al., 1993: Webb et al., 1994). Pre-industrial pH of precipitation in Virginia has been estimated to be from 5.3 to 5.6 (Webb, 1987). By 1996, precipitation pH readings at the Big Meadows water monitoring station in Shenandoah National Park, Madison County, Virginia averaged 4.4 (U.S. Environmental Protection Agency, 1998). This represents a tenfold increase in precipitation acidity since the beginning of the 20th century.

Acid deposition alone is not necessarily harmful to aquatic life. A watershed's ability to buffer acid precipitation determines whether the system suffers long-term biological degradation. Acid neutralizing capacity (ANC) is the ability of water to successfully neutralize additional acid ions. Desirable ANC levels for freestone headwater streams should be greater than 100 ueq/L (Webb, 1987). Once the finite ANC is completely exhausted, a stream no longer has the capability to neutralize incoming sources of acid and pH will decline. Under chronically acidic conditions, acid intolerant species are lost, leaving a less diverse community composed largely of acid tolerant species. Intense, bottom up alterations of food webs often occur in waters with acidic pH levels. (Hendrey, 1982). Increased mobilization of heavy metals such as aluminum, mercury, and lead from stream sediments has been documented in acidified waters (Baker, 1982). These metals, particularly aluminum, have been found to induce gas transfer complications in fish gills that can lead to asphyxiation (Leivestad, 1982). Reproductive development in fish can also be impaired in acidic environments (Peterson et al., 1982).

In 1987, a synoptic study of the water chemistry of 350 of Virginia's 450 wild trout streams, known as the Virginia Trout Stream Sensitivity Study (VTSSS), was conducted by the Virginia Department of Game and Inland Fisheries (VDGIF) in association with the University of Virginia's Department of Environmental Sciences. The result of that investigation indicated that over 78% of the sampled waters had ANC values <100 ueq/L (Webb, 1987). Of these "acid sensitive" streams, 11% were considered to be acidic (mean ANC values of zero or less). St. Marys River, once a premier wild trout fishery, was one of the watersheds in Virginia that fell into the acidified category.

Historic pH measurements recorded in St. Marys River through 1976 were consistently above 6.5 (Table 1). The one to two unit decline in mean pH levels during the eleven year gap between the last Department of Game and Inland Fisheries' pH test in 1976 and the beginning of the Virginia Trout Stream Sensitivity Study in 1987 clearly indicates that St. Marys River has become acidified.

St. Marys River has a long history of commercial, scientific, and recreational interest. In the 1910s, the Pulaski Iron Company built a railroad spur up the St. Marys River gorge to Chimney Branch (Fig. 1). The railroad served to transport manganiferous iron ore from excavated surface mines in the watershed to the Norfolk & Western Railroad siding at Pkin (Stose et al., 1919). The operation was abandoned after World War I but resumed briefly during World War II. Environmental damage to St. Marys River and some of its tributaries during the height of the mining operation was noted by the local populace but the watershed began to recover by 1935, when "a few nice trout" were noted in the pools of the main stream (Surber, 1951).

Scientists began examining the fauna of the St. Marys River watershed with the studies of Eugene Surber in the 1930s. In October 1936, Surber started a two-year investigation of water chemistry, stream flow, invertebrate

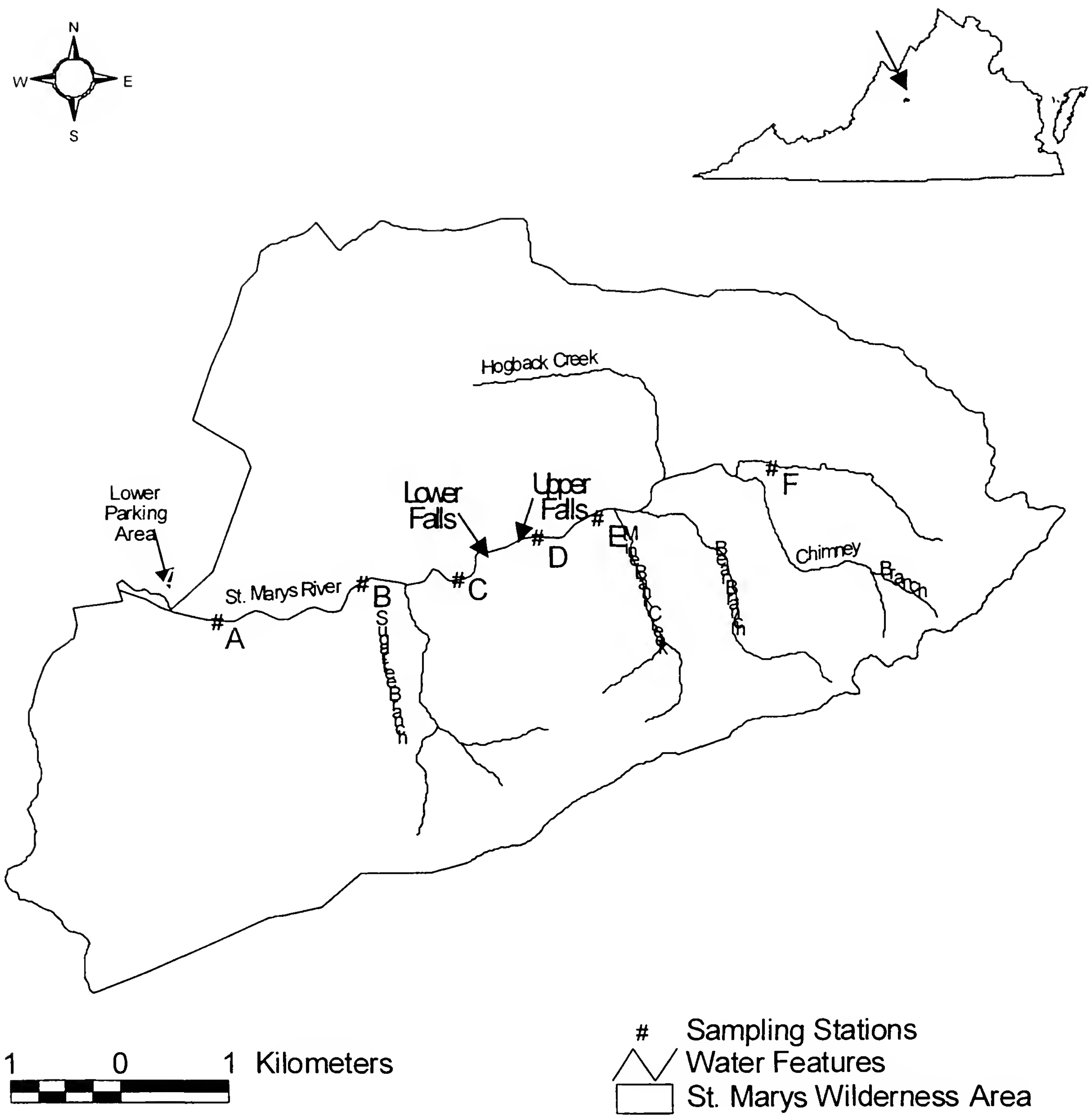


Fig. 1. Virginia Department of Game and Inland Fisheries sampling stations in the St. Marys River watershed, Augusta County, Virginia.

populations, and trout bioenergetics in St. Marys River (Surber, 1951). His study provided invaluable baseline data for future scientific endeavors. Although Surber closely examined water quality and macroinvertebrate populations, he did not sample fish populations in the watershed. Examination of angler catches generated the data for his bioenergetics work on trout. Chemical and flow information were collected in 1973 and 1974 by Trout Unlimited, and a creel survey was undertaken by Trout Unlimited in 1975 in order to quantify angler pressure and harvest on St. Marys River trout populations (G.D. Schuder, unpublished letter to VDGIF, 1976). As a result of these studies and other observations, St. Marys River became one of Virginia's earliest special regulation trout streams.

The Virginia Department of Game and Inland Fisheries' management activities in St. Marys River have ranged from the stocking of catchable trout to monitoring

Table 1. Historic and recent pH values for St. Marys River.

Year	Season	pH
1938	Summer	6.90
1938	Fall	6.70
1939	Spring	6.80
1973	Fall	7.00
1974	Spring	7.00
1974	Summer	6.90
1974	Fall	6.70
1976	Summer	6.80*
1976	Summer	7.00
1989	Winter	5.07*
1989	Winter	5.72
1989	Summer	5.15*
1989	Summer	5.69
1997	Winter	5.48
1997	Spring	5.68

*collected in upper watershed
1938-1939: pH was determined by unknown methods
1973-1976: pH was determined by Hach Model 17N colorimeter
1989-1997: pH determined electronically with Beckman Psi 21 pH meter

chemical and biological changes in the watershed. VDGIF stocked adult rainbow (*Oncorhynchus mykiss*) and brook trout (*Salvelinus fontinalis*) in St. Marys River from 1948 until 1974. This practice was discontinued due to severe access road damage caused by Hurricanes Camille and Agnes. In 1976 VDGIF staff conducted a comprehensive physical, chemical, and biological survey of the watershed as part of its statewide trout stream inventory project (Mohn & Bugas, 1980). These electrofishing surveys provided the earliest complete fisheries community study. Because the results of the 1976 investigation did not generate any immediate concern for more intensive work in the watershed, scientific investigation of the St. Marys River system was not pursued again by VDGIF until 1986. At that time the river was noted to be acidic, so VDGIF began biennial surveys of the fish and benthic communities (Kauffman et al., 1999). The United States Forest Service's (USFS) Coldwater Fisheries Research Unit from Virginia Tech conducted basinwide snorkel and electrofishing surveys in St. Marys River and the tributaries Mine Bank Creek, Chimney Branch, and Hogback Creek in 1989, 1994, and 1997 (P.A. Flebbe, personal communication). These surveys estimated total fish population size and determined fish distribution throughout the watershed by using visual quantification techniques.

In this paper, we have examined changes in the distribution, abundance, and density of fish species in St. Marys River over a 22 year period. The disturbing decline of fish in this watershed that are sensitive to low pH follows a similar pattern to other waterbodies that are exposed to acidic precipitation over long periods of time.

STUDY AREA

St. Marys River is a third order coldwater stream that drains the west slope of the central Blue Ridge Mountains in southeastern Augusta County, Virginia. It forms the southwest boundary of the Big Levels Management Area and its 27 km^2 watershed is the centerpiece of the 4,000 hectare St. Marys Wilderness Area. St. Marys River originates at 951 m above sea level and descends at a gradient of 39 m/km to its confluence with Spy Run, 11.4 km downstream. The watershed is comprised of five

Table 2. Electrofishing stations in the St. Marys River watershed, Augusta County, Virginia.

Station	Elevation (m)	Stream km from Wilderness boundary	Sample length (m)	Sample area (ha)
A	524	0.35	171	0.12
B	570	2.61	123	0.08
C	610	3.97	127	0.10
D	646	5.11	76	0.04
E	661	5.98	161	0.07
F	722	8.13	91	0.02

Table 3. Fish distribution in St. Marys River by sample year and sample station. Letter denotes uppermost station in the watershed where individual species were collected.

Fish Species	1976	1986	1988	1990	1992	1994	1996	1998
Brook Trout	F	F	F	F	F	F	F	F
Blacknose Dace	E	E	E	C	A	B	A	A
Fantail Darter	C	C	C	C	C	B	B	B
Mottled Sculpin	B	B	B	B	B	B	B	B
Rosyside Dace	B	B	B	B	A	B	A	
Torrent Sucker	C	B	B	B	B		A	
Rainbow Trout	E	E	C	C	C			
Longnose Dace	B	A			A			
Johnny Darter	A					A		
White Sucker	B	A						
Bluehead Chub	A			A				
Central Stoneroller		A						
Smallmouth Bass			B					
Brown Trout	C					A		
Total Species	12	10	8	8	8	7	6	4

major tributaries (Fig. 1). St. Marys River's low ANC levels can be traced to the geologic formations that underlie the watershed. Antietam quartzite is the primary rock formation (Werner, 1966). Formations of Hampton quartzite underlie the upper watersheds of Sugartree Branch, Mine Bank Creek, Bear Branch, and Chimney Branch, as well as the lower reach of St. Marys River. Both formations are known to have low solubility in water, thus providing few reactive materials to neutralize acidic input (Downey, 1994).

Dominant overstory vegetation in the St. Marys River basin include chestnut oak (*Quercus prinus*) and scarlet oak (*Quercus coccinea*) on ridges and north aspects, with pitch pine (*Pinus rigida*) and table mountain pine (*Pinus pungens*) dominating the southern and western slopes. Understory plants include mountain laurel (*Kalmia latifolia*), bear oak (*Quercus ilicifolia*), rhododendron (*Rhododendron maximum*), flowering dogwood (*Cornus florida*), red maple (*Acer rubrum*), and black gum (*Nyssa sylvatica*). Well drained, sandy loam covers most of the watershed, with the primary soil type being Drall-Hazleton-Leetonia. (Hockman et al., 1979). It is considered to be poor, acidic soil (Downey, 1994).

MATERIALS AND METHODS

In June 1976, VDGIF selected St. Marys River as one of 35 coldwater streams to be intensively studied as part of the Virginia Trout Stream and Environmental Inventory (Mohn & Bugas, 1980). Fisheries surveys were again conducted during late June of 1977, 1986, 1988, 1990, 1992, 1994, 1996, and 1998. Six sample stations were selected on St. Marys River from the lower Wilderness Area boundary to the headwaters (Fig 1.,Table 2). These sites were distributed throughout the mainstem starting from the Wilderness Area boundary and extending to the headwaters. Stations ranged from 76 to 171 m in length and included at least three sets of riffle, runs, and pools. Block nets (0.95 mm mesh) were set across the stream channel at the lower end of the station, while small waterfalls constituted the upper end of a site. A four person crew completed three electrofishing passes. All fish species encountered during each pass were netted and retained in individual holding pens by run. In 1976, fisheries work was completed with a shore-based 5 amp, 230 volt DC generator. This system was replaced with homemade battery powered backpack electrofishing units in the 1980s and from 1990 to present Smith-Root Model 12 battery powered backpack units have been used. After collected fish were sorted and counted by species, non-game fish were weighed in aggregate by species and released. All trout were measured to the nearest millimeter (mm), weighed to the nearest gram (gm), and released back into the stream. Population estimates were determined using the Maximum Weighted Likelihood Method with Microfish 3.0 software (Van Deventer & Platts, 1986). Stream width was measured at each station to calculate areas sampled.

Table 4. Biomass estimates in kg/ha for six fish species in St. Marys River, Augusta County, Virginia, 1976-1998.

	Year							
Species/Station	1976	1986	1988	1990	1992	1994	1996	1998
Brook trout								
A	0.8	3.4	3.2	10.1	15.3	6.4	5.4	9.0
B	9.3	10.7	18.7	19.0	16.1	10.4	7.6	25.1
C	6.4	6.0	9.4	19.6	9.9	15.7	3.0	20.1
D	0.7	1.2	0.6	21.3	26.6	2.4	8.1	57.3
E	6.3	6.2	4.3	16.0	26.2	10.3	17.7	19.7
F	27.2	10.7	1.1	16.5	8.4	2.1	5.9	1.1
Blacknose dace								
A	1.0	1.6	2.0	1.0	4.5	0.5	0.2	0.1
B	3.7	1.2	1.4	0.7	0.0	0.2	0.0	0.0
C	0.4	0.0	0.0	0.1	0.0	0.0	0.0	0.0
D	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E	1.4	0.1	0.1	0.0	0.0	0.0	0.0	0.0
F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Fantail darter								
A	0.3	1.0	0.1	0.3	0.4	0.5	0.1	0.1
B	1.7	0.1	0.7	0.1	0.0	0.0	0.0	0.0
C	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mottled sculpin								
A	0.8	1.2	2.2	11.9	1.6	1.3	0.4	0.4
B	0.1	1.3	8.7	0.7	0.1	5.7	0.3	0.1
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rosyside dace								
A	0.1	0.1	0.6	1.2	0.7	0.0	0.2	0.0
B	3.8	0.5	0.8	3.5	0.0	0.1	0.0	0.0
C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Torrent sucker								
A	2.1	1.2	2.9	4.1	10.9	0.0	0.1	0.0
B	5.7	3.6	2.9	3.4	0.0	0.0	0.0	0.0
C	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
E	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Rainbow trout								
A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C	1.3	0.0	7.7	1.7	2.7	0.0	0.0	0.0
D	16.1	3.9	0.0	0.0	0.0	0.0	0.0	0.0
E	4.4	4.5	0.0	0.0	0.0	0.0	0.0	0.0
F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

RESULTS

Fish Distribution

Fourteen fish species have been collected from St. Marys River and its major tributaries since 1976 (Table 3). Brook trout, blacknose dace (*Rhinichthys atratulus*), mottled sculpin *(Cottus bairdi)*, and fantail darter *(Etheostoma flabellare)* have been collected in all eight VDGIF surveys (Table 3). Rosyside dace *(Clinostomus funduloides)* were present in all of the surveys through 1996. Rainbow trout and torrent sucker *(Moxostoma rhothoecum)* were frequently encountered in their historic ranges through 1992. Since 1992, no rainbow trout have been collected in the St. Marys River watershed and only a single torrent sucker was captured in 1996. Fish species less frequently encountered include longnose dace *(Rhinichthys cataractae)*, brown trout *(Salmo trutta)*,white sucker *(Catostomus commersoni)*, bluehead chub *(Nocomis leptocephalus)*, central stoneroller *(Campostma anomalum)*, johnny darter *(Ethostoma nigrum)*, and smallmouth bass *(Micropterus dolomieui)* (Table 3).

Brook trout have been the most widely distributed fish species in the stream and have historically been collected at all six VDGIF sample stations (Table 3). Blacknose dace, a common coldwater stream cyprinid, was commonly found as far upstream as Station E through 1988, but its local distribution has been reduced to the lower reaches of the watershed in recent years. Distribution of fantail darters and torrent suckers have similarly been reduced to lower sample stations (Table 3). Mottled sculpins maintained their historic distribution patterns at sites A and B since 1976. Rosyside dace were frequently collected at Stations A and B over time, but were not found in the 1998 surveys.

Between Sugartree Branch and Mine Bank Creek, the gradient in St. Marys River increases to 43m/km and is

Table 5. Density estimates in number/km for three fish species in St. Marys River, Augusta County, Virginia, 1976-1998.

				Year				
Species/Station	1976	1986	1988	1990	1992	1994	1996	1998
Brook trout								
A	18	146	211	263	327	310	88	327
B	195	285	309	415	252	528	89	764
C	543	189	299	425	220	362	47	528
D	26	26	303	382	276	105	53	961
E	193	130	665	205	416	236	112	453
F	593	143	66	165	88	22	33	11
Blacknose dace								
A	164	427	719	298	1105	129	29	12
B	813	301	325	171	0	41	0	0
C	94	0	0	16	0	0	0	0
D	447	0	0	0	0	0	0	0
E	137	6	12	0	0	0	0	0
F	0	0	0	0	0	0	0	0
Rainbow trout								
A	0	0	0	0	0	0	0	0
B	0	0	0	0	0	0	0	0
C	110	0	94	31	24	0	0	0
D	289	92	0	0	0	0	0	0
E	75	37	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0

characterized by numerous large waterfalls and deep plunge pools. It was in this reach that rainbow trout, a naturalized holdover from early stocking programs, remained in St. Marys River through 1992. Rainbow trout were found at Stations C, D, and E in 1976, Stations C and D in 1988, and only at Station C in 1990. Rainbow trout have not been collected in the last three VDGIF electrofishing surveys.

The remaining fish species were less frequently collected; their abundance was low, and distributions were generally limited to the lower stations (Table 3). Smallmouth bass are considered to be an occasional transient in the lower reaches. Brown trout, another stocking holdover, were collected as far upstream as Station C in 1976, but their range has been reduced to the deep pool habitat of Station A. Like the rainbow trout, brown trout have naturalized in St. Marys River and appear to prefer the lower reaches of the watershed. Brown trout were relatively abundant in 1976 and in 1977 but only one has since been collected (in 1994).

Fish Abundance

The fish community in St. Marys River has changed dramatically since 1976 (Table 4). Brook trout is the dominant predatory species and the only indigenous salmonid in St. Marys River. In 1976, it was well distributed throughout St. Marys River and its major tributaries. Brook trout biomass ranged from 0.6 kg/ha at Station D in 1988 to 57.3 kg/ha at Station D in 1998 (Table 4).

Rainbow trout were moderately abundant at Stations C, D, and E in 1976 but have not been seen since 1992. A total of seven brown trout were collected at Stations A, B, and C in 1976 and four were found in 1977 at stations A and B during a partial survey of the river. Brown trout were last collected from the watershed in 1994. Blacknose dace biomass declined precipitously over the duration of the study (Table 4). This species was common in 1976 up to Station E (1.4 kg/ha). By 1986, only a few individuals were collected in the watershed above Sugartree Branch. Blacknose dace were abundant at Station A (4.5 kg/ha) in 1992 and relatively abundant at Station B (0.7 kg/ha) through 1990, however, a total of only five individuals were collected at Station A and none at Station B in both 1996 and 1998. Mottled sculpin have been fairly abundant at Stations A and B, but biomass has notably declined at both of these sites since 1994 (Table 4). Fantail darters historically populated St. Marys River in moderate numbers up to Station C. Station B has not produced a fantail darter since 1990 and Station C yielded a single specimen in 1992. Except for a single specimen found in 1996, torrent suckers have not been seen since 1992. Rosyside dace was a common component of the fish community at Station A through 1992 and at Station B through 1990. However, only one specimen was collected in 1994, four were collected in 1996, and none were found in 1998.

Brook trout numbers remained stable from 1988 through 1994, but dropped considerably in 1996 (Table 5). The population rebounded to a historic high in 1998 but most of the population consisted of a single year class (100-150 mm) spawned during the dry winter of 1996 (Fig. 2). Station A is currently the only sample site where blacknose dace are regularly collected. Blacknose dace densities reached an historic level of 1,105 fish/km in 1992, but declined to 12 fish/km in 1998. Table 5 shows that this species was abundantly distributed in the watershed to Station E in 1976, but populations have since declined dramatically in number and range. Rainbow trout numbers were strong at Stations C, D, and E in 1976 (Table 5), but 10 years later densities dropped critically. The rainbow trout were last collected at Stations D and E in 1986, and at Station C in 1992.

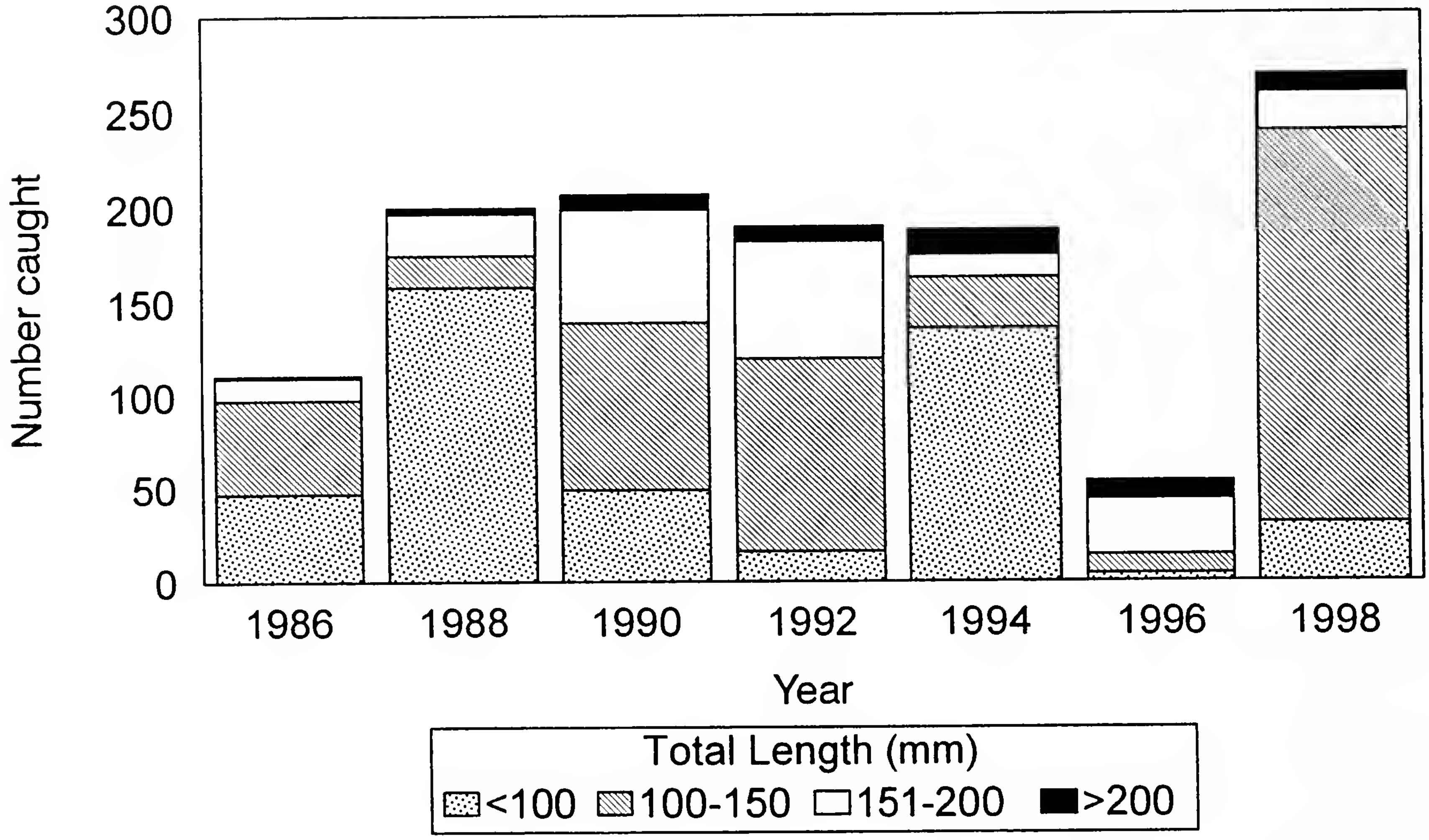
DISCUSSION

Fish abundance, species diversity, and distribution patterns in St. Marys Rivers have been dramatically altered since 1976. In 1998, VDGIF monitoring produced only four fish species: brook trout, blacknose dace, fantail darter, and mottled sculpin, a loss of two-thirds of the 12 fish species collected in 1976. Seven fish species were consistently represented in the 1976-1992 surveys (Table 3), but of those, rainbow trout have subsequently disappeared from our samples and only one torrent sucker has been collected (in 1996). Rosyside dace, historically another common species of both Station A or B, was not found in 1998. Brown trout were frequently encountered up to Station C in 1976 and were found in a qualitative VDGIF survey in 1977, but both their numbers and distribution have been reduced over time. In 1994, a single brown trout was found at Station A, possibly indicating a small, remnant population still existing in the lower watershed.

Brook trout are the most acid tolerant of all fish species that reside in St. Marys River, but populations begin to decline when pH consistently remains at 5.0 or lower (Schneider, 1986). Despite current acidic conditions, they remain distributed throughout St. Marys River.

Rainbow trout and blacknose dace are two among the most acid sensitive fish species in the watershed. Population loss begins to occur at a pH of 6.0 for both species (Magnuson, 1983; Schofield & Driscoll, 1987). Rainbow trout have not been collected since 1992 and are assumed to be gone from the system (Table 4, 5). Blacknose dace were historically found in moderate densities up to Mine

Fig. 2. Composition of biennial samples of brook trout by size classes in St. Marys River, Augusta County, Virginia, 1986-1998. Samples represent total number of individuals in all stations combined.



Bank Creek. Today, blacknose dace distribution is limited to Station A (and in some unnamed tributaries) where pH and ANC levels are somewhat higher than in the upper watershed. Blacknose dace density at Station A has also declined dramatically since 1992. During their 1989 and 1994 snorkel surveys, USFS researchers found blacknose dace distributed between Sugartree Branch and Mine Bank Creek, but none was found in their 1997 survey (P.A. Flebbe, personal communication). These researchers calculated that basinwide blacknose dace abundance dropped from 182 individuals in 1989, to 18 in 1994, and to zero in 1997. Mottled sculpin abundance and distribution in St. Marys River has remained relatively unchanged since 1976. Mottled sculpins are moderately sensitive to decreasing pH levels (Rahel & Magnuson, 1983). Recruitment failure in the slimy sculpin (*Cottus cognatus*), a species that requires similar environmental conditions as the mottled sculpin, begins in waters with a pH between 5.3 and 5.8 (Magnuson, 1983). Information about acid sensitivity of the remaining St. Marys River fish species is lacking. The extirpation of rainbow trout, coupled with sharp declines in blacknose dace and other non game fish populations, is symptomatic of aquatic environments that are poorly buffered against the effects of acid precipitation.

Brook trout spawn in the fall and eggs or sac fry remain in redds for up to four months (Jenkins & Burkhead, 1994). During this period, nests are frequently exposed to episodic flushes of acidic water. In acidified waters, a wet winter and early spring often result in poor egg or fry survival and increased natural mortality. Such was the case in St. Marys River during the winters of 1994/95, 1995/96 and 1997/98. Low survival from 1994/95 and 1995/96 year classes resulted in a small 1996 population of brook trout (Fig. 2). Young-of-the-year brook trout were abundant in 1994 (Fig. 2) and contributed to a strong spawning population (>150 mm) during fall of 1996. This large spawning population, combined with low flows throughout the winter of 1996/97 resulted in an abundance of young-of-the-year brook trout (D. Kirk, personal communication) in the St. Marys watershed in 1997. These fish survived to form a significant component of the 1998 survey and are represented in Fig. 2 as 100-150 mm fish (1+ year old). Although the brook trout in the St. Marys River watershed are currently abundant, successful reproduction has occurred only once in the past

four years due to an unusually low flow fall and winter that minimized episodic acidic pulses.

From 1976 to 1998, the number of fish species in St. Marys River declined from 12 to 4. Of the species remaining, densities of some species are severely reduced and brook trout reproduction appears to be sporadic. Historic fish distribution patterns within the watershed for all species, except brook trout, have been altered during the survey period. This study shows that a twenty two year decline in the fish community of St. Marys River has occurred as a result of anthropogenic acid deposition. Although the brook trout population appears to be less affected by acidification than the other species, it remains vulnerable due to the interaction of life history, flow regimes, and acidification.

To forestall further water quality degradation in St. Marys River, the U. S. Forest Service has proposed to add approximately 140 tons of limestone sand to the five major tributaries and in St. Marys River near Station F (D. Kirk, personal communication). The goal of this action will be to artificially raise pH to a mean level of 6.5 (A. Christensen, USFS Environmental Assessment, 1998). With improved water quality, St. Marys River should temporarily provide a environment suitable for re-establishment of its indigenous aquatic organisms, as well as improve the brook trout population to a level where the river will reclaim its reputation as one of Virginia's premier trout fisheries.

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Streamside Salamanders in an Acidic Blue Ridge Mountain Stream: Historical Comparisons and Relative Abundance

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INTRODUCTION

Headwater streams in the mountainous region of western Virginia have a high potential for acidification as a result of anthropogenically-generated acidic deposition (Cosby et al., 1991). The primary source in the Shenandoah Valley of Virginia is rain that is about ten times higher in acid concentration than unpolluted rainfall (Webb et al., 1989a). Acidification of surface waters is a problem where sulfate adsorption capacities of catchment soils are exhausted by continued acid deposition and when soils and underlying bedrock provide little buffering capacity to neutralize the acidity (Galloway et al., 1983; Webb et al., 1989b). St. Marys River in Augusta County, Virginia, lies within the region of acidic deposition in the Appalachians and is underlain by bedrock of the Antietam Formation, a low solubility quartzite, with minimal buffering capacity. Water quality analyses in St. Marys watershed have demonstrated reductions in acid neutralizing capacity (ANC) and consequent increases in acidity (Webb et al., 1994, 1999).

Water chemistry and changes in the fauna of St. Marys River have been the subjects of a number of scientific investigations (e.g., Surber, 1951; Webb et al., 1989b; Kaufmann et al., 1993, 1999; Mohn et al., 1993; Bugas et al., 1999). During 1935-1937, E.W. Surber conducted studies on aquatic insects in this system (Surber, 1951). These data provide the baseline for continued investigations on benthic macroinvertebrates and the benchmark against which declines in species richness and abundance have been measured (Kauffman et al., 1999). Likewise, the fish fauna has been the subject of investigations for over 20 years, and similar declines in richness and abundance have been documented (Mohn et al., 1993; Bugas, 1999). Declines in invertebrates and fish are reportedly the result of increasing anthropogenic acidification (Camuto, 1991; Feldman & Conner, 1992).

In contrast to fish and invertebrates, the amphibian fauna has received little study. It is unknown whether these animals have responded in similar ways as the fish and invertebrates. The only historical information available is Surber's density estimates from the total number of unidentified salamanders captured in his standardized samples. To obtain insights into the streamside salamander fauna, we conducted inventory and monitoring surveys in St. Marys River mainstem and two tributaries in 1997 and 1998. These data serve as an initial baseline for relative abundance and densities of salamanders.

MATERIALS AND METHODS

We monitored streamside salamander assemblages with two methods: (1) quantitative substrate samples to obtain density estimates to compare with Surber's data and (2) time-constrained visual encounter surveys (Heyer et al., 1994) to obtain relative abundance data. We obtained three quantitative substrate samples using a

Carle® sampler at each of six sites along the St. Marys River on 24-25 June 1998 (Fig. 1). Each sample was collected in a riffle area. The substrate was agitated for several minutes to obtain salamanders from the substrate matrix. Carle® samplers are similar to Surber® samplers, except the sampling area is larger and salamanders cannot wash out around the net, thus increasing capture success. Surber's original data were presented as organisms/ft^2 but we transformed them into salamanders/m^2 for comparison to our data.

We conducted time-constrained visual encounter surveys during 1997 and 1998. These were performed at three sites along the St. Marys River mainstem (Lower, Middle, and Upper) and at two tributaries (Sugartree Branch and Bear Branch) (Fig. 1). Two to three sample plots were searched at each site and each plot was at least 10 m long and 100 m from other plots. During sampling, we turned over all surface objects and searched all microhabitats that might harbor amphibians. Sample time per plot was 0.5 h. We identified and captured where possible all individuals encountered, recording snout-vent length (SVL) and tail length to the nearest mm with a plastic ruler for each animal. Location and dates on which visual encounter surveys were conducted included: Lower St. Marys - 9 September 1997, 13 August 1998; Middle St. Mary's - 17 October 1997, 12 August 1998; Upper St. Mary's - 9 October 1997, 11 August 1998; Sugartree Branch - 15 October 1997, 13 August 1998; Bear Branch - 14 October 1997, 11 & 12 August 1998.

We did not collect quantitative habitat measurements at each visual encounter survey site but we did record qualitative site descriptions. One third of all sites had a canopy closure of >50%. Substrate type was dominated by cobbles and boulder (42% of all sites), with cobble and bedrock (33%) and cobble and gravel (25%) occurring in fewer sites. No one stream section was dominated by a single substrate type.

RESULTS

Comparison to Historical Data

Surber (1951) collected 19 benthic samples (20 replicates each) monthly between August 1935 and August 1937. Total benthic salamander density within that time frame averaged 2.8±1.5 salamanders/m^2 and varied by month and season (Fig. 2). Winter (November-January) salamander densities averaged 4.5 salamanders/m^2 (4.0 to 5.8) and summer (June-August) densities averaged 2.0 salamanders/m^2 (0.6 to 4.8). The difference between seasons is significant (t-test, t = -3.22, P = 0.011). Average salamander density in June 1936 was

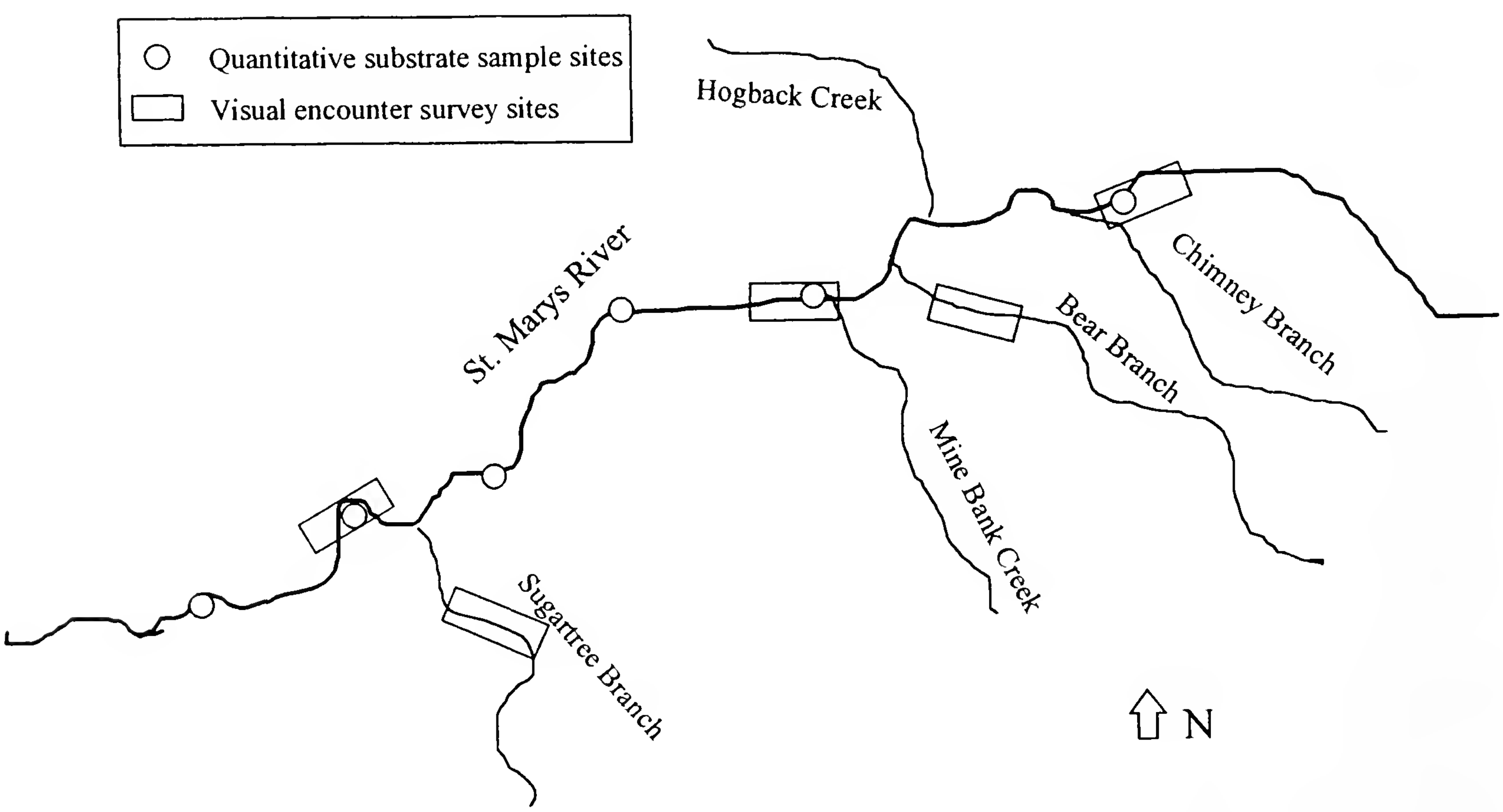

Fig. 1. Quantitative substrate sample sites and visual encounter survey sites along the St. Marys River and two tributaries, Augusta, County, Virginia.

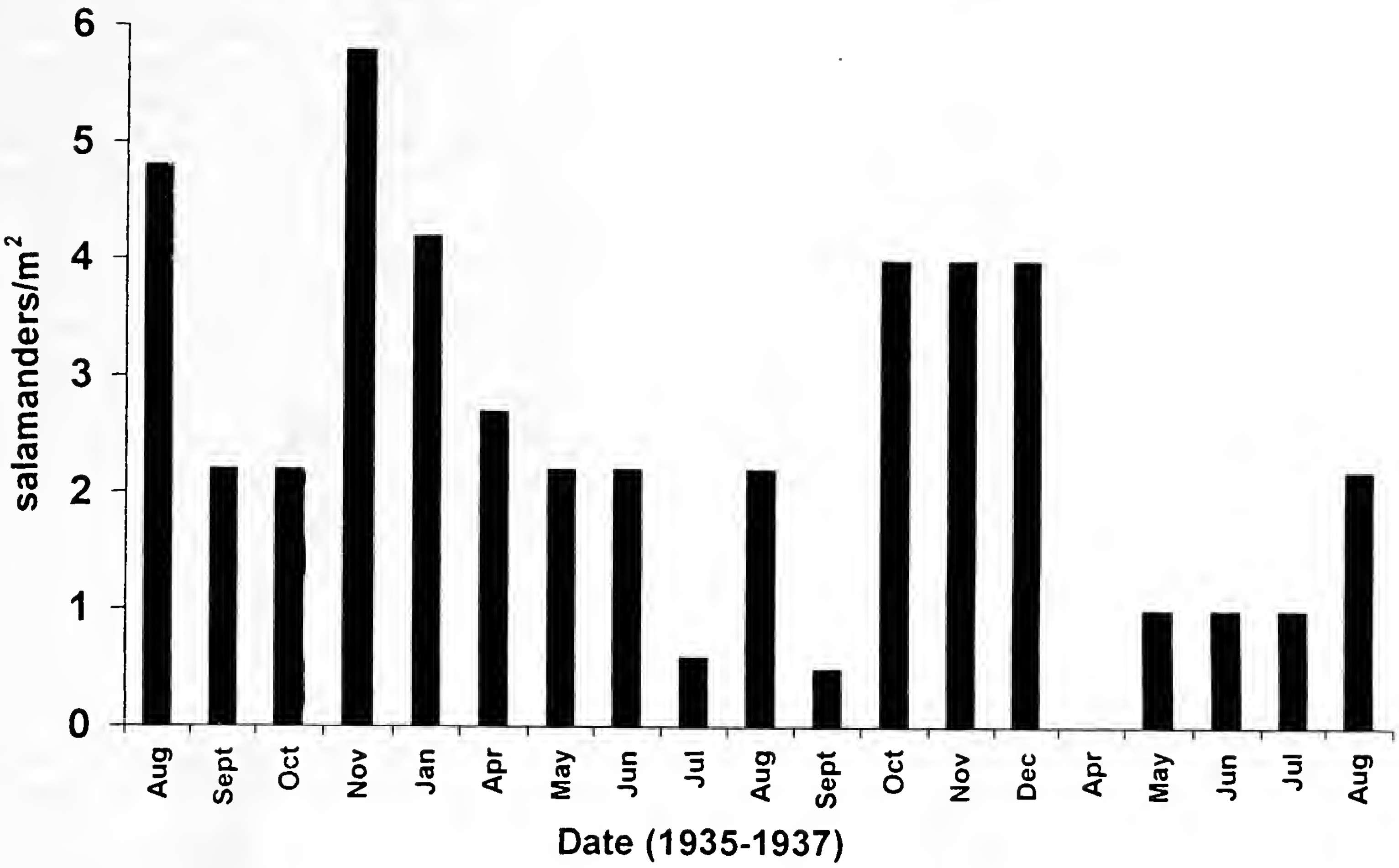

Fig. 2. Benthic salamander density in the St. Marys River, 1935-1937, based on data in Surber (1951). No data were provided for missing months.

2.2/m^2, whereas in June 1937 it was 1.0/m^2. Our sample in June 1998 (mean = 0.6 salamanders/m^2) was not significantly different from either of the earlier June samples ($P > 0.5$).

Species Composition

We encountered all four species of streamside salamanders typical of streams in this section of the Blue Ridge Mountains of Virginia north of the James River (Mitchell, 1998): *Desmognathus fuscus*, *D. monticola*, *Eurycea cirrigera*, and *Gyrinophilus porphyriticus*. In addition, we encountered several terrestrial *Plethodon cinereus* near the water's edge. This species is not included in our comparisons. All four species were encountered during 1997 in different frequencies during visual-encounter surveys: *D. monticola* (39%), *G. porphyriticus* (22%), *D. fuscus* (21%), and *E. cirrigera* (17%). Only 3 species were found during the 1998 visual-encounter surveys. These samples were also dominated by *D. fuscus* (56%) and *D. monticola* (40%), with only a few *G. porphyriticus* (4%). No *Eurycea* were found in 1998.

Size Structure and Relative Abundance

Size structure of streamside salamander populations was determined using SVL measurements from captured individuals. Minimum body sizes at maturity (SVL, based on Petranka, 1998), used to define adults in this study, was 33 mm for *D. fuscus*, 48 mm for *D. monticola*, and 61 for *G. porphyriticus*. All *E. cirrigera* captured were adults. Many more adult *D. monticola* and *G. porphyriticus* were found in 1997 than 1998 (Fig. 3). Juvenile salamanders dominated samples in 1998.

Relative abundance of all salamander species (combined data) was higher at all sample sites in 1998 than in 1997 (Fig. 4). In 1997, abundance was highest in the tributaries (Bear Branch 11/h, Sugartree Branch 8/h), and lowest in Middle St. Marys (1/h). Relative abundance was also high in Bear Branch (23/h) and Sugartree Branch (21/h) in 1998. The Lower St. Marys river mainstem site had the lowest relative abundance in 1998 with 6/h.

DISCUSSION

Composition of the streamside salamander assemblage in the St. Marys watershed appears to be the same as that

in other Blue Ridge Mountain streams in the area. Streams affected similarly by acid precipitation in Shenandoah National Park (SNP) supported populations of the same species of salamanders during 1995-1998 (Mitchell, 1998). The only species found in the SNP study that was not encountered in the St. Marys watershed is the northern red salamander (*Pseudotriton ruber*). Sampling effort is the likely explanation since *P. ruber* was rarely encountered in SNP. Thus, it appears that there has been no loss of salamander species in the St. Marys system, in contrast to losses of some invertebrates and fish (e.g., Kaufmann et al., 1999; Bugas et al., 1999).

Our June 1998 salamander density was not significantly lower than 1936 or 1937 densities, suggesting that salamanders have apparently not declined in abundance over the 60 year period. However, sample sizes were small and we currently do not have enough trend data to determine if any real changes have occurred. However, within this 60 year timeframe, water quality, specifically pH, has decreased substantially and there have been subsequent negative effects on the fish and invertebrate communities in the St. Marys watershed (Kauffman et al., 1999; Bugas et al., 1999). These changes parallel those documented elsewhere in the Appalachian region (Arnold et al., 1981; Herrmann et al., 1993; Guerold et al., 1995; Griffith et al., 1995).

The greater proportion of juvenile salamanders encountered in 1998 compared to 1997 may be the result of either greater reproductive success that year or a function of sample date. Samples in 1997 were taken in

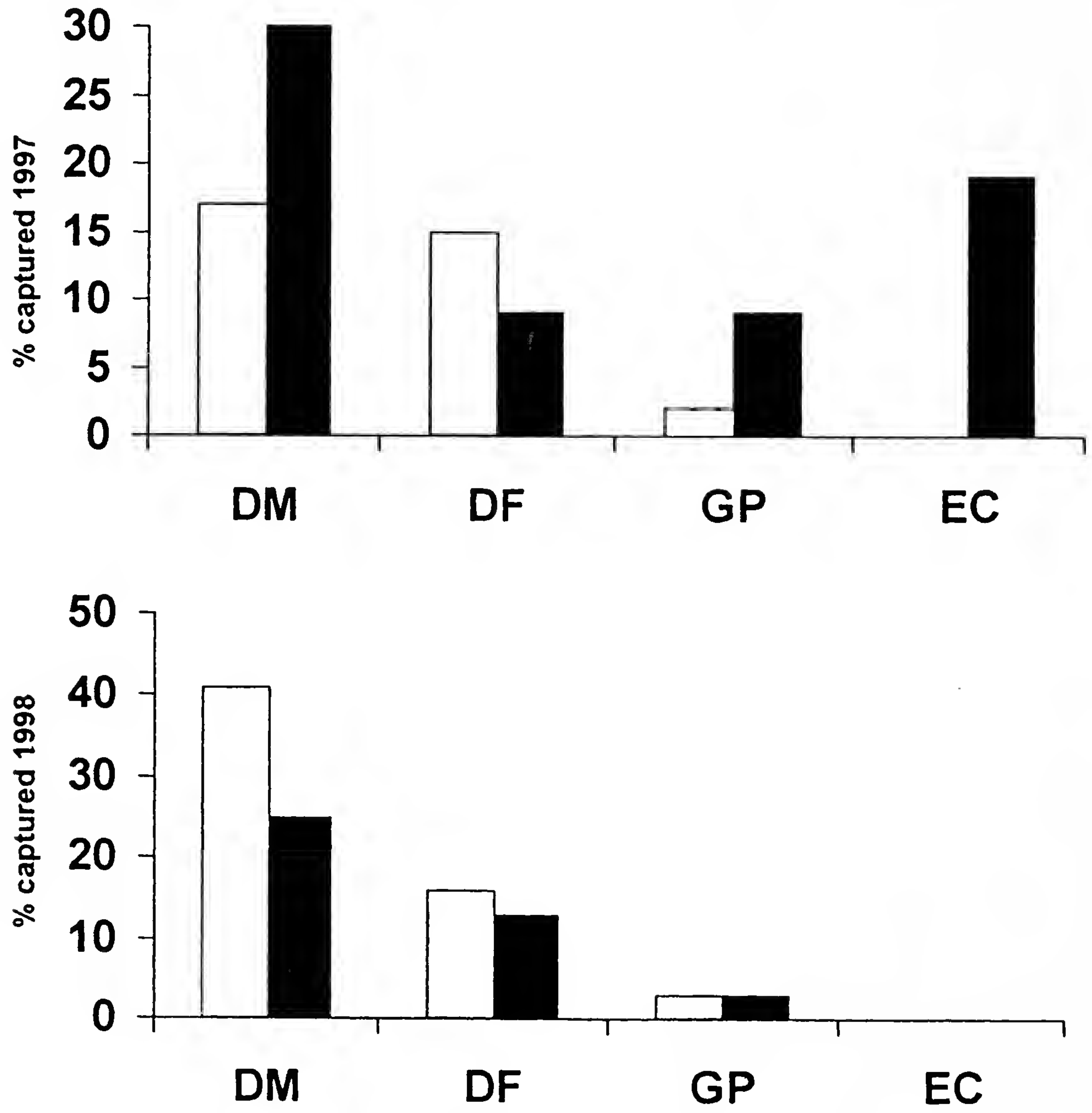

Fig. 3. Age structure of streamside salamander samples in St. Marys River and two tributaries, Augusta County, Virginia. Open bars represent juveniles and larvae and closed bars represent adults. Percent is % of all salamanders captured in each year. Abbreviations: *Desmognathus fuscus* (DF), *Desmognathus monticola* (DM), *Eurycea cirrigera* (EC), *Gyrinophilus porphyriticus* (GP).

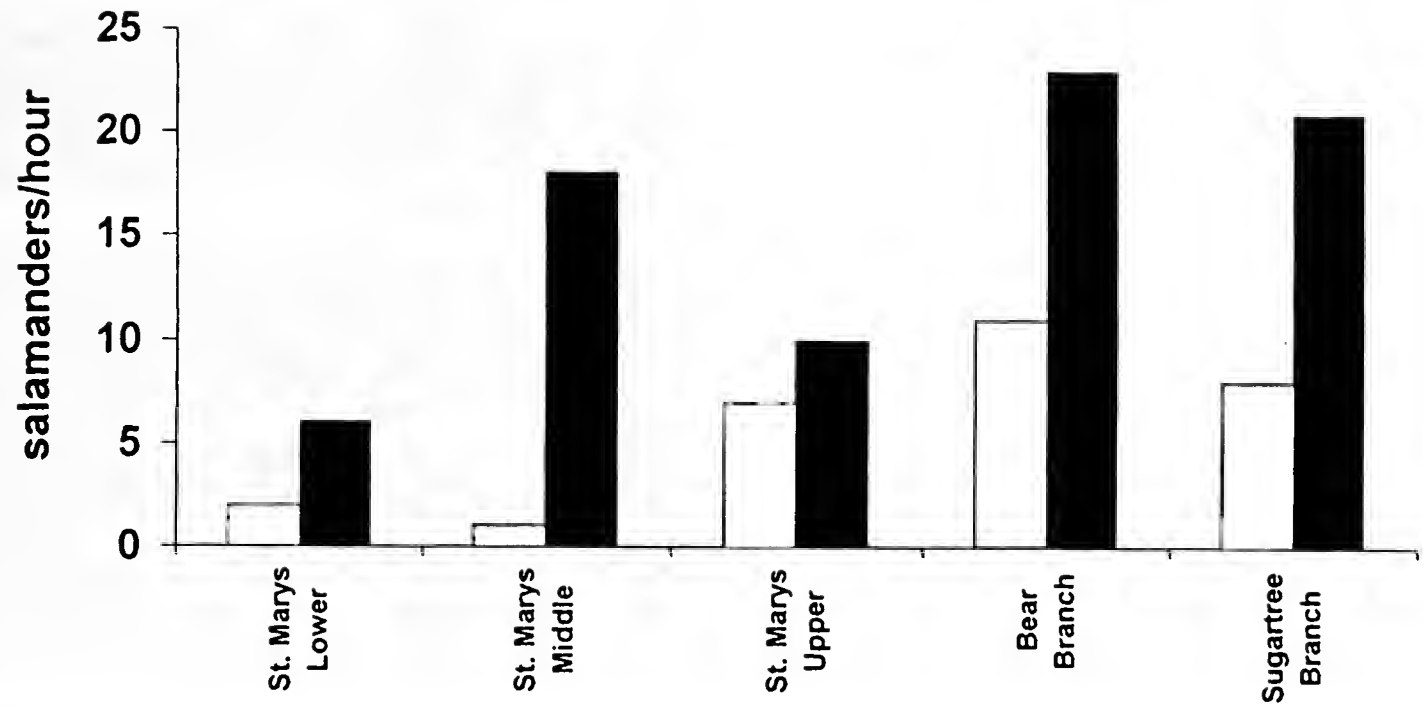

Fig. 4. Relative abundance of salamanders in St. Marys River and two tributaries by sample site for 1997 and 1998. Open bars represent 1997 samples and closed bars represent 1998 samples.

late September and early October, during which time fallen leaves in the stream made searching difficult. In 1998, sampling was conducted in August to avoid this problem. Occurrence of juveniles in both years demonstrates that streamside salamanders are experiencing reproductive success in St. Marys watershed. However, we do not know recruitment rates and how these numbers compare to historic trends.

Salamanders appear to be more tolerant of acidic conditions than some invertebrates and fish. They have been shown to reproduce in water with pH levels above *ca.* 4.5-5.0 and suffer a variety of effects at levels below pH 4.5 (Sadinski & Dunson, 1992; Horne & Dunson, 1994; Kutka, 1994). However, indirect effects on salamander survival and reproductive success could occur as the aquatic flora and fauna changes around them in response to increased acidity. These changes include a decreased nutritious food base as macroinvertebrate abundance and richness decreases (Arnold et al., 1981; Herrmann et al., 1993; Guerold et al., 1995), as microbial decomposition or detrital material is slowed (Tuchman, 1993), and as the planktonic and algal communities experience shifts toward more acid-tolerant species (Herrmann et al., 1993). An additional indirect effect is a reduction of predation by fish on salamander eggs and larvae as fish species abundance decreases or are extirpated (Resetarits, 1991, 1995).

Variation in stream habitats in various parts of watersheds (e.g., mainstem sections and tributaries), as well as presence or absence of predators are known to affect the composition of streamside salamander communities (Southerland, 1986; Resetarits, 1991). Relative abundance data from 1997 and 1998 suggest that streamside salamanders are more abundant in the tributaries and higher elevations in the watershed than in the lower reaches of the mainstem of St. Marys River. This is the reverse of the distribution of pH values and fish abundance (Webb et al., 1999; Kaufmann et al., 1999; Bugas et al., 1999). In our study, salamanders are more abundant where acidic conditions have negatively affected fish abundance and richness. This distributional relationship suggests that salamanders are responding positively to the reduction in predation. However, it is also possible that habitats differ enough among sites to affect abundance, with the better salamander habitat being in the tributaries and upper reaches of the mainstem. However, habitat variables we measured did not apparently vary enough among sites to limit salamander abundance at the downstream sites. These scenarios suggest hypotheses that could be tested with additional quantitative surveys and monitoring efforts. Long-term monitoring using our standardized methods should be used to develop inferences about population trends.

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Shorter Contributions

Abstracts from the Big Levels Symposium

Banisteria, Number 13, 1999

LONG-TERM VEGETATION AND FIRE HISTORIES AT SPRING POND, VIRGINIA – Both long-term vegetation and fire histories were reconstructed for the region surrounding Spring Pond, Virginia for the last 18,000 years. Pollen grains and charcoal particles were identified and quantified in a 2.20 meter long core in order to reconstruct the past vegetation and fire histories. A series of AMS radiocarbon dates were used to determine sedimentation rates and a time chronology. The results from the pollen analysis showed that three major vegetation communities (*Pinus-Picea*, *Quercus*, and *Quercus-Pinus*) have occupied the forest surrounding Spring Pond since full-glacial. From 18,000 to 10,000 years BP, a conifer forest dominated by *Pinus* and *Picea* occupied the site. Low abundances of charcoal were found in the sediment during this period, indicating the low importance of fire. A sharp transition between the Pleistocene and Holocene periods (10,000 year BP) marks the replacement of the conifer forest by a *Quercus-Tsuga* dominated community. The persistence of low charcoal flux at the transition suggests that fire was not an important factor during this vegetation shift. However, these results differ from other regional sites (Brown Pond, VA and Trout Pond, W.VA) where charcoal abundance increases sharply at that transition. The *Quercus-Tsuga* forest occupied the community surrounding Spring Pond until 6,000 BP when *Tsuga* declined and *Pinus* re-emerged. This established the *Quercus-Pinus* dominated community of modern times. Charcoal flux increased during the reemergence of *Pinus*, suggesting a greater importance of fire during the *Quercus-Pinus* period.

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PREHISTORY OF BIG LEVELS: 12,500 YEARS OF CULTURAL EVOLUTION – Big Levels and environs have been occupied by humankind for approximately 12,500 years. Human use, however, has varied through time both in intensity and with function. The earliest groups utilized the environment over extensive territories within a central based wandering pattern and possibly a higher reliance on hunting than in later periods. As the Pleistocene became the Holocene, settlement and subsistence activities evolved into a seasonal round focusing on needed commodities as they became available. As band level groups of 25-50 people, the hunters and gatherers were egalitarian with community relations based on achieved as opposed to ascribed status. Gradually, the prime subsistence strategies emphasized plants with a clear sexual division of labor. Until circa 2500 BC, settlement patterns were sylvan in nature exploiting a broad environmental spectrum. At that time, the major drainages became the focus with floodplains and terrace systems the central place of settlement and subsistence emphasizing white-tailed deer, seed crops, nuts, and fish. The beginnings of horticulture occurred during this time with an ever-increasing reliance on raised crops. By AD 900-1000, the triad of corn, beans, and squash formed the basis of foodways supplemented by continued hunting and fishing. The more fertile floodplains were the cultural focus for the gardening of crops, the location of towns and villages, and the interplay of tribal-level societies.

Big Levels was occupied from circa 8000 BC through the contact period. The major use of the area, however, occurred during late Archaic times from about 2500-1000 BC. In addition to hunting and gathering opportunities, the outcrops and secondary deposits of quartzite were extensively used for the production of stone tools. Unique environmental attributes of Big Levels during the Xenothermic may have led to other exploitation of the area. Recent excavations at 44AU548, a quartzite quarry

site, recovered a tool assemblage involving extensive spear point and shaft production.

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LATE CENOZOIC HISTORY OF ALLUVIAL FANS NEAR STUARTS DRAFT, VIRGINIA– Large coalescing alluvial fans mantle the carbonate and shale formations west of the Blue Ridge Mountains near Stuarts Draft, Virginia. U.S.A. Fan deposits contain mostly cobble-to-boulder gravels derived predominately from the Antietam Quartzite. The fan complex consists of at least three mappable alluvial units of different ages with distinctive combinations of clast weathering, soil profile characteristics, and degree of stream incision. Planar or weakly conical surfaces exist onfans of all ages, although stream incision, slope retreat, and scattered sinkhole formation have progressively destroyed these depositional surfaces through time. Well drilling records indicate that fan deposits exceed 100 meters thickness over the Shady Formation carbonate beds but may be as little as 3 meters thick over adjacent clastic units. Stratigraphic data, electrical resistivity surveys, statistical analyses of weathering criteria, and distribution of fan surfaces indicate that fluvial deposition occurred during discretepulses separated by prolonged periods of weathering and landscape stability. Periodic capture of the upland streams by piedmont streams and solutional lowering of fan surfaces near the mountain front combined to isolate old, deeply weathered fan remnants at the distal edges of the fan complex; much of the youngest, competent fan sediment lies near the mountain front. Comparison of soil development and clast weathering of fan sediments with dated Coastal Plain deposits permits order-of-magnitude age estimates. This comparison suggests that the youngest fan deposits are latest Pleistocene, the intermediate-age deposits may range from late Pleistocene to late Pliocene, and the oldest fan surfaces may be as old as Pliocene or Miocene.

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Muscipula Regia, s.
Lychnis viscosa flore
amplo coccineo.